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Contents

8423-01, Session 1

Science meets magic: photonic metamaterials

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The word “magic” is usually associated with movies, fiction, children stories, etc. but seldom with the natural sciences. Recent advances in metamaterials have changed this notion, in which we can now speak of “almost magical” properties that scientists could only dream about only a decade ago. In this article, we review some of the recent “almost magical” progress in the field of metamaterials.

8423-02, Session 1

Low loss metamaterial lens

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Since Pendry’s theoretical proposition of the perfect lens, extensive researches have been carried out in this field to create super-resolution devices. After Zhang’s group first demonstrated the superlens by using a thin silver slab workable in ultraviolet (UV) spectrum. Several other groups demonstrated similar lenses using different materials and structures. Recently, multilayered structures and metal particle chain-like structure were also proposed by several groups. The major problems associated with the lenses are the large ohmic loss and narrow transmission spectrum. In this talk, we present and discuss the low loss metamaterial lenses with novel structures. Such lenses can transfer image to a much longer distance with a wide spectrum in visible range and are capable of high magnification and high resolution.

8423-03, Session 1

Dark mode excitation in asymmetric planar optical metamaterial dimer

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Tailoring the properties of metamaterial has led to the demonstration of exotic properties such as negative index, electromagnetic cloaking, electromagnetically induced transparency etc, which are usually not present in naturally occurring materials. These metamaterial properties have made them very attractive for research and future applications as well. One important realizable feature of metamaterials is the excitation of dark or subradiant modes. These dark modes, unlike the bright modes in symmetric structures, couple very weakly to free space and are therefore not easily excitable by incident radiation. As a result these modes have low losses and posses a high Q-factor, therefore making them interesting in applications such as sensors. Such dark modes can be excited by introducing asymmetry in the structure. In this work we numerically study the dark and bright modes in a planar metamaterial dimer structure composed of gold deposited on ITO coated glass substrate. The metamaterial unit cell structure is made up of gold dimer whose length axis have been arranged side by side. A normal incident wave with polarization along the dimer axis is incident on the metamaterial dimer. In the symmetric dimer configuration with equal lengths of gold nanorods, high frequency bright resonant modes with broad profiles are easily excited due to their strong coupling to free space. These bright modes are dipole-like in nature with an in-phase current distribution in both arms of the dimer. Introducing asymmetry in the dimer with a unequal length of the nanorods, the dark mode which were absent in the symmetric structure are excited and the coupling of these modes to the bright modes produces a Fano type resonant profile. The narrow profile dark mode displays a characteristic asymmetric current distribution in both arms of the dimer. We show that these dark modes strongly depend on the asymmetry of the dimer with the high Q-factor rapidly decreasing with asymmetry, unlike the bright modes whose low Q-factor shows very little dependence on asymmetry. The high Q-factor of theses dark modes makes them interesting for possible applications as sensors. Finally, we also show that the dominant factor in the excitation of the dark modes, that is the introduction of asymmetry in the length of the nanorod, is independent of the way it is introduced. Introducing asymmetry by symmetrically varying the length of a nanorod of the dimer from both ends or asymmetrically inducing the length reduction of the nanorod from only one end shows similar properties of the dark modes.

8423-04, Session 1

Sub-wavelength structured illumination

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Structured illumination or higher order beams have found many applications in microscopy, plasmonics, metamaterials and more generally optical interactions. Most generally, it consists in the creation of optical fields that have special properties with respect to a specific interaction. Higher order beam, such as the Airy beams, Bessel beams and Laguerre-Gaussian beams show particular usefulness in specific circumstances. However, the general question arises of the existence of a beam profile or structured illumination for each device or interaction considered. Here, we build on the optical eigenmode method to show that it is possible to define such device or interaction specific beam that is capable to create sub-wavelength illumination features. We apply this approach to assess the far field and near field resolution limit in the context of nano-photonic devices.

8423-05, Session 1

Metal-dielectric metamaterials for guided optics applications

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The aim of the present work was to investigate the potential of metallic metamaterials (MM) for building optical functions in guided wave optics at 1.5µm. The undertaken approach consists in considering a composite guiding structure made of a MM layer over a high index slab waveguide, as for instance silicon in our case. In such a configuration only the evanescent tail interacts with the MM layer which acts essentially as a perturbation. The numerical simulations show that an array of gold coupled cut wires over a slab waveguide leads to a significant variation of the slab effective index in the vicinity of the resonance.

To apply the effective medium approximation, the coupling between consecutive rows of cut wires must be dominant with respect to all other interactions in the system. This implies using small separation distances, below 100nm, between the cut wires. The resulting effective index contrast is around 0.5 for a 100nm thick Si slab and around 0.25 for a 150nm thick Si slab. Such an index contrast is high enough for implementing a variety of optical functions.

In certain cases, such as in transformation optical devices, it is desirable to design MMs with a strong degree of anisotropy. We showed that the anisotropy of our hybrid MM waveguides can be increased by inserting a thin dielectric layer with a low index of refraction between the cut wires and the Si slab. This intermediate layer makes it possible to increase the length of the cut wires without shifting the resonance frequency, thus maximizing their aspect ratio and anisotropic response.

A critical aspect of the considered problem is related to the MM absorption losses which are on the order of a few dB per microns. To minimize the absorption losses, we followed the usual procedure that consists in detuning the resonance frequency from the operating frequency. However, this approach reduces the range of effective indices that can be attained. One possible way to counteract this issue is to consider multi-layer structures of coupled cut wires.

The obtained results represent a first step toward building optical function in guided wave optics using hybrid metallo - dielectric metamaterials.

8423-92, Session 1

Isotropic properties of the photonic bandgap in quasicrystals with low-index contrast

A. Andreone, G. Abbate, E. Di Gennaro, P. T. Rose, Univ. degli Studi di Napoli Federico II (Italy)

Photonic quasicrystals (PQCs) have neither true periodicity nor translational symmetry, however they can exhibit symmetries that are not achievable by conventional periodic structures. The arbitrarily high rotational symmetry of these materials can be practically exploited to manufacture isotropic band gap materials, which are perfectly suitable for hosting waveguides or cavities. In this work, formation and development of the photonic bandgap (PBG) in 2 dimensional 8-, 10- and 12-fold symmetry quasicrystalline lattices of low dielectric contrast (0.4-0.6) were studied and compared with the PBG properties of a conventional hexagonal crystal. Band-gap properties were also investigated by changing the direction of propagation of the incident beam inside the crystal. Various angles of incidence from 0° to 30° were used. The effect of the crystal thickness on the PBGs was also studied. Simulations were done using a two-dimensional Finite Difference Time Domain (FDTD) method with Perfectly Matched Layer (PML) boundary conditions. Experiments were carried out in the microwave range 8-20 GHz using a pair of horn antennas and a vector network analyzer (HP 8720C). Rexolite (dielectric constant 2.56) rods of radius 0.32 cm and length 60 cm were used to build up the structures. The filling factor of all the structures was fixed to 0.23. All measurements were carried out for the TE polarization of the incident radiation. Both simulations and experimental results show that the photonic band-gaps formed by the quasicrystal structures, because of the higher order of rotational symmetry, are more isotropic in comparison with the conventional periodic crystal having a hexagonal geometry. They also exhibit a higher robustness of the PBG when reducing the crystal thickness. The low index contrast allows the use of versatile and low-cost technologies like holographic lithography combined with soft materials for the development of compact devices with switchable properties for an all-optical ultrasmall integrated circuitry.

8423-06, Session 2

Chiral and multifunctional meta-materials

T. Verbiest, W. Brullot, V. Valev, Katholieke Univ. Leuven (Belgium)

We will give an overview of our recent work on the design of multifunctional meta-materials and chiral meta-materials. The chiral materials are composed of chiral nano structures deposited on Si that where characterized by nonlinear optical techniques. Our results show peculiar interparticle coupling behavior resulting in extremely strong optical activity effects. This behavior could be exploited for the design of negative refractive index materials.

For the multifunctional meta-materials we will focus on periodic structures composed of super paramagnetic layers alternated by layers composed of plasmonic materials. We will demonstrate that such systems show great promise as sensing material.

8423-07, Session 2

New design methodologies for negative index, chiral, and broadband light harvesting metamaterials

S. A. Maier, Imperial College London (United Kingdom)

This talk will discuss two recent approaches for creating optical metamaterials. Firstly, we will show how block copolymer self-assembly of chiral gyroid networks can be used to create 3D, isotropic negative index metamaterials. Full-field electromagnetic simulations of this geometry reveal that the choice of metal is crucial for the occurrence of negative refraction. We show how subtle changes in the underlying gyroid network allow us to tune the spectral region of negative refraction, and to create chiral metamaterials.

Secondly, we will present concepts to create nanoplasmonic cavities with the hallmark of a broadband light harvesting response, based on transformation optics. As singular features (touching points of metallic nanostructures) are crucial for the occurrence of the broadband response, we then investigate the consequences of spatial non-locality on the light harvesting, and experimentally answer the question down to which gap size classical electromagnetism is sufficient to describe the plasmonic mode spectrum. Using electron energy loss spectroscopy on nanoantennas, we confirm that the classical approach is valid down to separation distances of about one nanometer. These findings can find use in the design of novel planar metamaterials for broadband light collection.

8423-08, Session 2

Helical assemblies of plasmonic nanorods as chiral metamaterials

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Nanoscale chiral architectures of metallic components attract growing interest in relation to negative-index metamaterials and also because of their huge optical activity which exceeds by several orders of magnitude that of naturally occurring chiral materials, thus opening new perspectives in the design of functional components for miniaturized optical devices. In the present communication we propose and analyze a layer-by-layer assembly of metallic nanorods, with circular cross section, stacked along the z direction. In each layer the nanorods are centered at the sites of a square lattice with their axes aligned perpendicular to the z direction and mutually twisted through an angle of 60 degrees from layer to layer. We report a thorough investigation of the optical properties of this crystal by means of rigorous full electrodynamic calculations using the layer-multiple-scattering method, properly extended to describe axis-symmetric particles with arbitrary orientation. The photonic bands of the crystal along its [001] direction are non-degenerate and have the symmetry of the two irreducible representations of the C2 point group, which are not spanned by purely left- and right- circularly polarized (LCP and RCP, respectively) eigenmodes. All bands belong to the odd irreducible representation and have a different degree of LCP and RCP admixture that varies along a specific band. Therefore, anticrossing interaction between the bands always takes place and gives rise to hybridization-induced gaps, the size of which depends on the shape of the modes involved. The photonic dispersion diagram reveals the existence of (a): two extended bands, one of LCP and one of RCP predominant character, associated with wave propagation in an underlying effective medium and (b): three narrow bands, i.e., as many as the number of nanorods per primitive cell, originating from the fundamental longitudinal dipole-like plasmon modes of the individual nanorods weakly interacting between them. We provide a consistent interpretation of the formation of these narrow bands in terms of the hybrid modes of the trimer plasmonic molecule of twisted nanorods. Our results also reveal the existence of negative group-velocity bands that can lead to negative refraction, as explained through a detailed and systematic analysis of the relevant isofrequency contours. Moreover, we demonstrate the occurrence of polarization selective extinction over the partial gap regions. Over a frequency range of a polarization gap, only incident waves of opposite handedness are allowed to pass through, which implies strong circular birefringence and dichroism. We show that multilayer slabs of the given crystal exhibit strong optical activity and circular dichroism, combined with reduced dissipative losses, which make the proposed structure potentially useful for practical applications as ultrathin circular polarizers and polarization rotators.

8423-87, Session 2

Localized modes, Fano resonances, and embedded states in nonlinear magnetic metamaterials

M. I. Molina, Univ. de Chile (Chile)

We examine some of the basic phenomenology found in a 1D magnetic metamaterial modeled as a split-ring resonator array:

(1) Existence of linear and nonlinear localized modes around single bulk and surface magnetoinductive impurities. We examine a number of simple defect configurations where the localized magnetoinductive mode can be found in closed form. We also look at the dynamical diffusion of an initially localized magnetoinductive bulk excitation and prove that it is ballistic at all times. For a surface excitation, the diffusion is shown to converge to a ballistic propagation after a transient time.

(2) Scattering of magnetoinductive plane waves by internal (external) capacitive (inductive) defects coupled to a one-dimensional magnetic metamaterial. We compute in closed form the transmission coefficient and determine conditions under which there are Fano resonance, and how to tune them by varying simple external parameters. We find that for embedded capacitive defects, the addition of a small amount of coupling to second neighbors, is necessary for the occurrence of Fano resonance. For external inductive defects, Fano resonances are commonplace, and they can be tuned by changing the relative orientation/distance between the defect and the SSR array.

(3) Finally, we describe a method for building a localized magnetoinductive mode embedded in the linear band of extended states of the split-ring resonator array. The embedded mode is shown to have structural stability and its position inside the band can be tuned by adding weak nonlinear effects.

All of this phenomenology stems from the discrete and periodic character of the magnetic metamaterial model and can also be found in many other systems.

8423-88, Session 2

Tunable Josephson metamaterials

P. Jung, S. Butz, Karlsruher Institut für Technologie (Germany); S. V. Shitov, National Univ. of Science and Technology "MISiS" (Russian Federation) and Kotelnikov Institute of Radio Engineering and Electronics (Russian Federation); A. V. Ustinov, Karlsruher Institut für Technologie (Germany) and National Univ. of Science and Technology (Russian Federation)

We report on recent experiments with superconducting Josephson metamaterials. There are two features, which set this class of microwave metamaterials apart from the conventional approach: The use of superconductors instead of normal metals in the resonating elements to reduce dissipation and the application of Josephson junctions as nonlinear inductors.

We are going to present data from experiments in which conventional split ring resonators have been replaced by one-dimensional arrays of superconducting loops with Josephson Junctions (RF-SQUIDs) as the magnetically coupled building blocks of the metamaterial. The SQUID arrays are situated in the gap of a coplanar waveguide with their loop area perpendicular to the magnetic eld direction. In this case, the Josephson inductance and thus the resonance frequency of the elements depends on the magnetic flux in the SQUID loop that is induced by a current through the central conductor of the waveguide. Conventional metamaterials are usually limited to a certain operating frequency by choice of the design parameters.

In contrast, superconducting Josephson metamaterial is tunable in frequency. In combination with similar electrically coupled elements, both the eective electric permittivity and magnetic permeability can be tuned within a certain range for a given frequency. The ability to directly influence the fundamental properties of electromagnetic wave propagation of the medium also oers a multitude of potential applications in the field of low-temperature microwave electronics and superconducting circuits.

8423-90, Session 2

Complete optical absorption in periodically patterned graphene metamaterials

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We predict 100% light absorption in a single sheed of periodically patterned doped graphene. Specifically, we show that arrays of doped graphene nanodisks display full absorption when supported on a substrate under total internal reflection and also when lying on a dielectric layer coating a metal. Our results are relevant for infrared light detectors and sources, which can be made tunable via electrostatic doping of graphene.

8423-09, Session 3

Three-dimensional metamaterials: from nano bumps to erected U-shape nano-rings and toroidal metamaterials in optical region

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Fabrication of nano bumps and erected split ring resonators (SRRs) on a fused silica substrate has been successfully fabricated by laser and e-beam lithography process, respectively. The plasmonic resonance modes of such plasmonic nanostructures also investigated both by finite-element simulations and optical measurements, which are in excellent agreement with each other. We found that, as surface plasmon incident to nano-bumps, the scattering light is focused to a focusing spots with sub-wavelength size around 330 nm and the property of focusing spot strongly depends on the geometry arrangement of nano-bumps. The off-plane U-shape SRR structures was fabricated by double e-beam lithography with precise alignment technique (under 10 nm miss-alignment) to investigate the plasmonic resonant modes of three dimensional metamaterials. Comparing with the other methods of fabrications for off-plane U-shape SRRs, our approach provides the smaller size as well as the better resolution of SRRs; however, the height of SRR structures is limited by the thickness of resist in our approach. From simulation results, we find electromagnetic field solely depends on the resonance mode either enhanced between two prongs or around two prongs of single erected U-shape gold nano rings. The magnetic interaction in three dimensional metamolecules also results in extraordinary electromagnetic properties, such as toroidal dipole response. By analyzing the electromagnetic distribution in near-field region at optical frequency, we found toroidal resonance and magnetic resonance generated by the magnetic dipole of each metamolecule. These research results have potential to be applied in the area such as the integrated photonic circuit, plasmonic sensing and plasmon rulers in optical frequency region.

8423-11, Session 3

Self-organized eutectic and metal-dielectric nanoplasmonic composites: manufacturing and properties

D. A. Pawlak, M. Gajc, K. Bienkowski, A. Klos, K. Sadecka, A. Stefanski, B. Surma, Institute of Electronic Materials Technology (Poland)

We report on a paradigm for fabricating nano and microstructured engineered materials for photonics (metamaterials, plasmonics) by self-organization. The materials are made through: (i) directional solidification of eutectics and (ii) directional solidification of dielectrics doped with metallic nanoparticles in a non-chemical process. The obtained materials exhibit novel controllable electromagnetic functionalities such as plasmonic resonances at visible and IR wavelengths, enhanced luminescence, enhanced nonlinear susceptibilities.

One of the future ways of obtaining materials with unusual electromagnetic properties or metamaterials most probably will be methods based on self-organization. Eutectic solidification is a clear example of a process where self-organization mechanism leads to patterned materials. That is why it has been recently proposed that directionally solidified self-organized eutectic structures could show metamaterial properties. Eutectics form micro and nanostructures with the controllable size ranging from micro to nano regime. Eutectics are versatile: (i) they are simultaneously monolith and multiphase, (ii) they can be formed out of various component materials enabling design of potential on-demand metamaterial (oxides, metals, semiconductors, ferroelectrics, ferromagnetics, nonlinear materials, active materials), (iii) they can form various structural motifs, such as fibrous/rodlike, lamellar, globular, percolated, and others. The method which we utilize to grow the eutectics allows manufacturing of bulk material samples. The directional solidification enables also manufacturing plasmonic nanocomposites by doping dielectric matrix with various metallic/semiconducting nanoparticles. Materials with potential for subwavelength transmission and focusing in infrared range, directional thermal emission management, photoactive materials for solar hydrogen production, and 3D bulk nanoplasmonic composites will be discussed.

8423-12, Session 3

Fabrication of 70-nm split ring resonators by nanoimprint lithography

G. J. Sharp, A. Z. Khokhar, N. P. Johnson, Univ. of Glasgow (United Kingdom)

We report on the fabrication of 70 nm wide, high resolution rectangular U-shaped split ring resonators (SRRs) using nanoimprint lithography (NIL). By patterning SRR shaped structures in hydrogen silsesquioxane (HSQ) on silicon and hardening them in a furnace we imprint directly into PMMA, negating the need for etching the silicon substrate. We then proceed with the deposition and lift-off of aluminium to construct the structures and measure an LC resonance peak under transverse electric (TE) conditions at the near ultraviolet range of the visible spectrum. Measurements of the SRRs in transverse magnetic (TM) mode are also taken to complement the TE response. Fabricating the SRRs by NIL rather than conventional electron beam lithography allows them to be scaled to smaller dimensions without any significant loss in resolution, partly because backscattered electrons and the proximity effect are not present with NIL. This in turn helps to shift the magnetic response to lower wavelengths while still retaining a distinct LC peak. Therefore fabricating spit ring resonators in this way allows for experimental verification of previous simulated work into the limits of scaling SRRs below dimensions of 100 nm. In addition to aluminium SRRs, we also measure and compare gold SRRs fabricated by the same method.

8423-13, Session 3

Left-handed Maxwellian aspects of natural pearl

A. K. R. Sarkar, A. Sarkar, A. Gangopadhyay, Bijoy Krishna Girls' College (India)

Pearl is a bio-originated valuable natural gem and it is also cultivated or harvested for jewellery. It is a natural nano-composite with inhomogeneous amorphous nature in calcite and proteinous background. In this paper, the optical/ photonic aspects of pearl have been investigated experimentally. In a recent study it has been found [1] that it has a layered structure with very high static dielectric constant. The beautiful iridescence of natural pearl is due to the presence of very small sized nano-particles and may be explained by nano-optics. Various optical aspects and parameters of pearl bead are analyzed experimentally. Optical reflectance and absorbance on pearl surfaces was studied carefully and also compared with that from pearl powder. The later exhibits no Left Handed Maxwell (LHM) property. The optical band gap for layered pearl surface has been estimated about 310 nm. The preliminary surface reflection experiment on pearl bead with polarized laser beam indicates that it is a type II or type III like natural LHM system [2]. Recently LHM property has been observed [2] in natural Mica. The observed photonic nature and its beautiful luster are due to presence of small sized inorganic nano-clusters in it. The present work concludes that pearl has LHM nature like meta materials.

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References: [1]. S.S. Pradhan and A. Sarkar, Journal of Biomimetics, Biomaterials & Tissue Engineering Vol.11 (2011) pp 1-12.

[2]Aditi Sarkar, Arnab Gangopadhyay and A. Sarkar, Modern Physics Letters B, Vol. 25, No. 30 (2011) 2323-2333 .

8423-65, Session 3

Nano-antenna for greatly enhanced THz emission in a photomixer

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The continuous wave (CW) THz technology has the advantages of high spectral resolution, fast response, tunability and low cost. Despite the significant progress in THz science and technology, there is still a lack of compact room temperature operated high power THz source, which will greatly benefit many of the THz applications especially the narrow bandwidth high resolution spectroscopy and imaging. One promising technique to realize CW THz emission is by using photomixing in ultra-fast photoconductive semiconductor materials. It has the advantage of providing frequency tunable and narrow-bandwidth THz output. However, the key challenge is to improve the THz emission efficiency and power. Metamaterials have provided unique opportunities for manipulating electromagnetic wave in THz range. Many novel THz devices have been demonstrated such as frequency agile filters and modulators, perfect absorber and collimation of a THz quantum cascade laser beam. In this talk, I will give a brief review of the possible CW THz generation methods followed by the introduction of the nano-antenna enhanced THz emission in a LTGaAs based photomixer. The nano-gap electrode introduced to the photoconductive antenna active region can greatly enhance the localized THz field and act as a nano-antenna to radiate the THz wave. It also provides good impedance matching to the THz planar antenna and exhibits a lower RC time constant allowing more efficient radiation especially at the higher part of the THz spectrum. As a result, the new source demonstrated an output power of two orders of magnitude higher than the photomixer with typical interdigitated electrodes. The results have significant impact on the development of more efficient CW THz sources for compact THz imaging and sensing applications. Besides, THz polarizer made on semiconductor substrate using different materials with the potential of tuning and integration with the CW THz source will also be discussed.

8423-14, Session 4

Quantum plasmon resonances of individual and coupled metallic nanoparticles

J. A. Dionne, J. A. Scholl, A. L. Koh, Stanford Univ. (United States)

The plasmon resonances of metallic nanoparticles have received considerable attention for their applications in nanophotonics, biology, sensing, spectroscopy, and solar energy harvesting. While thoroughly characterized for spheres larger than 10 nanometers in diameter, the plasmonic properties of particles entering the quantum size regime (~2-10 nm) have been historically difficult to describe. Quantum-sized plasmonic particles not only exhibit very low extinction cross-sections, but the observed plasmon resonances are also typically blurred by surface-ligand interactions and inhomogeneity in ensemble measurements. Such difficulties preclude plasmonic control of quantum-sized particles, which are arguably the most relevant to many natural and engineered processes, notably catalysis.

In this presentation, we investigate the plasmon resonances of individual ligand-free silver nanoparticles using aberration-corrected transmission electron microscope (TEM) imaging and monochromated scanning TEM electron energy-loss spectroscopy (STEM EELS). This technique allows direct correlation between a particle's geometry and its plasmon resonance. As the nanoparticle diameter decreases from 20 nm to less than 2 nm, the plasmon resonance exhibits a blue-shift from 3.3 eV to 3.8 eV, with particles smaller than 10 nm showing a substantial deviation from classical predictions. We present an analytical quantum-mechanical model that well describes the plasmon resonance shift due to a change in particle permittivity. Our results highlight the unique quantum plasmonic properties of small metallic nanospheres, with direct application to understanding and exploiting catalytically-active and biologically-relevant nanoparticles.

Furthermore, using TEM EELS, we can observe the plasmonic properties of multi-particle systems. Using excitation from the electron beam, ligand-free silver particles are capable of moving on silica substrates, allowing dynamic monitoring of plasmonic resonances as the particles approach each other and coalesce. This strategy provides a straightforward method for studying dimer interactions at variable separation distances, including quantum-sized separations. Because individual sets of particles can simultaneously imaged and spectrally analyzed, we can directly probe the crossover from classical to quantum plasmon resonances in particle dimers.

8423-15, Session 4

Repulsive Casimir forces and quantum levitation in exotic media

S. I. Maslovski, M. G. Silveirinha, Instituto de Telecomunicações (Portugal)

Since theoretical discovery of the Casimir effect in 1948 by Hendrik B. G. Casimir, it remains a topic of active discussion in various areas of research that deal with fluctuating quantum fields. In quantum electrodynamics, the Casimir effect is due to the zero-point fluctuations of the electromagnetic field. These fluctuations exist everywhere, however, in search for a macroscopic effect, one typically considers an electromagnetic resonator or a cavity and solves for the free energy of the quantum-electromagnetic fluctuations in it. Then, the Casimir effect appears as the response of the system to a change in the geometry of the cavity.

Typically, the Casimir effect results in an attractive force between bodies with similar electromagnetic properties. The Casimir repulsion between dielectric objects that differ in permittivity may occur when such objects are immersed in a dielectric fluid. There exist also geometries in which dielectric bodies may repel each other in vacuum, however, such geometries are generally unstable if motion of the bodies is not restricted.

Additional possibilities emerge when Casimir effects in metamaterials are considered. For instance, we have recently found that the Casimir forces between dielectric objects in a uniaxial background formed by metallic nanowires can be very strong and extremely long range when compared to the same forces in vacuum [Phys. Rev. A 82, 022511 (2010)]. Moreover, in geometries involving cut silver nanorods standing in air, it is possible to obtain strong enough repulsive Casimir forces that may compete gravity and allow for the so-called quantum levitation [Phys. Rev. A 83, 022508 (2011)]. Casimir repulsion exists also in layered moving media, in which the amplitude and the sign of the force strongly depend on the relative velocities of the layers [Phys. Rev. A 84, 022506 (2011)].

In this talk we will discuss several possibilities that may lead to the Casimir repulsion and levitation phenomena, especially when the Casimir interaction is mediated by various exotic media.

8423-16, Session 4

Cooperative response in ordinary and superconducting planar metamaterials

J. Ruostekoski, S. Jenkins, Univ. of Southampton (United Kingdom)

In metamaterial systems of closely-spaced meta-molecules, electromagnetic and plasmonic fields can mediate strong interactions between the resonators. In that case the metamaterial system responds to incident fields cooperatively, exhibiting collective modes of current oscillation. Such collective eigenmodes of the system cover a broad range of different resonance frequencies and radiative emission rates some of which may dramatically differ from those of an isolated unit-cell resonator. We show that in large systems of asymmetric split-ring resonators (ASRs) the collective effects can be numerically analyzed using a computationally efficient model based on a multipole expansion of radiative interactions between discrete resonators. We find that collective effects due to strong field-mediated interactions between the resonators provide the characteristic feature in the recent observations [1] of a spectral collapse in the transmission resonance of a planar metamaterial array: the cooperative response of sufficiently closely-spaced resonators generates the observed dramatic narrowing of the transmission resonance linewidth with the number of resonators. The analysis of the system in terms of the properties of a collective mode with suppressed radiative emission rates provides physically simple explanation of the experiment, together with an excellent agreement between numerical results and the observations. We also address cooperative response in metamaterial systems formed by superconducting SQUID resonators in which case the response of an individual resonator can be strongly nonlinear.

The collective effects find several potential applications in understanding the dynamics and design of novel meta-materials. We present an example in which case an asymmetry in the meta-molecule geometry provides an effective coupling between the collective modes opening a transparency window in the material. In contrast with similar phenomena based on electromagnetically-induced transparency that can be described by meta-molecules acting independently, here the effect relies on cooperative interactions to form the high quality modes responsible for the transparency.

[1] V. A. Fedotov et al., Phys. Rev. Lett. 104, 223901 (2010).

8423-17, Session 4

Metamaterials can suppress Anderson localization of light in one dimension

F. A. Pinheiro, Univ. Federal do Rio de Janeiro (Brazil); D. Mogilevtsev, B.I. Stepanov Institute of Physics (Belarus); R. dos Santos, Univ. Federal do Rio de Janeiro (Brazil); S. Cavalcanti, Univ. Federal de Alagoas (Brazil); L. Oliveira, Univ. Estadual de Campinas (Brazil)

Advances in metamaterials have allowed the development of unusual optical properties, opening up new frontiers in photonics. Amongst several issues related to these properties, the question of Anderson localization (AL) of light in disordered media containing metamaterials is still not fully understood. Here we discuss light propagation through 1D disordered structures composed of alternating layers, with random thicknesses, of air (A) and a dispersive metamaterial (M). While it is generally expected that, in ordinary disordered media, the vast majority of waves should become localized in one-dimension, we show that in the case of light, its vector character, together with the intrinsic dispersion present in metamaterials, leads to interesting particularities in AL. Indeed, we have established that Anderson localization of light may be suppressed: (i) in the long wavelength limit, for a finite angle of incidence which depends on the parameters of the dispersive metamaterial; (ii) for isolated frequencies, and for specific angles of incidence, corresponding to Brewster anomalies in both positive- and negative-refraction regimes of the dispersive metamaterial. On the other hand, in the long wavelength limit, the localization length tends to a constant value for sufficiently large angles of incidence, in contrast to what is generally expected for disordered systems. We have also found that delocalization at the very edge of a band gap is possible, a result which could be explored to observe slow light propagation in disordered photonic structures. We also discuss the effects on the photonic gaps brought about by correlation in the disorder, and compare with the uncorrelated case; we consider the completely correlated (i.e., the A and M layer are subject to the same fluctuation in width) and anticorrelated (the total width of the A+M double layer is constant) cases.

8423-86, Session 4

Graphene: a novel platform for capturing and manipulating light at the nanoscale

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Graphene, a two-dimensional sheet of carbon atoms, has recently emerged as a novel material with unique electrical and optical properties. Graphene has zero band gap, high-mobility charge carriers with an effective mass of zero and - despite its thickness of a single atomic layer - it still absorbs significant (~2.3%) light in the visible and near infrared region. Because these unique characteristics are all present in one material, graphene has great potential for opto-electronic applications, such as ultrafast photo-detection and optical switches.

In this talk, I will review recent experimental work on exploiting graphene as a host for guiding, switching and manipulating light and electrons at the nanoscale. This is achieved by exploiting surface plasmons: surface waves coupled to the charge carrier excitations of the conducting sheet. Due to the unique characteristics of graphene, light can be squeezed into extremely small volumes and thus facilitate strongly enhanced light-matter interactions. I will discuss recent observations of propagating and localized optical plasmons in graphene nano-structures. The plasmon wavelength can be tuned and plasmon propagation can even be switched on and off in-situ, simply by tuning the carrier density by electrostatic gates. These results pave the way towards ultrafast modulation of nanoscale optical fields, resonantly confined in graphene nano-structures or propagating along graphene ribbons.

8423-18, Session 5

Highly sensitive optical detection of organic materials using asymmetric split ring resonators

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Asymmetric split ring resonators (A-SRRs) are formed when two separate metallic arcs of different lengths share the same centre-of-curvature. The resonances of the two arcs interact to produce steep slopes in the reflection spectrum. By depositing very thin films of poly-methyl-methacrylate (PMMA), a shift in resonance reflection spectra is obtained. Similarly, it is known that the spectral position of the A-SRR resonances can be tuned with size. We show that, when PMMA is used as an organic probe (analyte) on top of an A-SRR array, the phase and amplitude of a characteristic molecular bond resonance associated with PMMA changes the appearance of the observed Fano resonance, according to the spectral position of the plasmonic reflection peaks. This effect can be utilized to give characteristic signatures for the purpose of detection. We also show the effectiveness of localizing different blocks of PMMA at different places on the A-SRR array to detect very small amounts of non-uniformly distributed analytes. Finally we show that even though the resonance Q-factor is much smaller when compared to values achievable in photonic crystal microcavities, the plasmonic nano-antenna arrays can be used to provide highly sensitive detection of organic compounds.

8423-19, Session 5

Electromagnetic field sensors hidden from the field source

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The theory and realization of material objects which are “invisible” when observed from any direction as well as the concept of cloaking have attracted considerable interest in the literature. However, objects which do not scatter any power also do not absorb any power, so it is not possible to realize an “invisible sensor”. This is obvious from the optical theorem which relates the total extinction cross section with the scattering amplitude in the forward direction. Therefore, in the design of sensors of electromagnetic fields we must allow nonzero power scattered at least in the forward direction, but it is possible to reduce scattering in the other directions. In the design of sensors of electromagnetic fields it is desirable to minimize backscattering from the sensor towards the field source, minimizing interference between the sensor and the object under study. It is known that objects manifesting zero backscattering for incident waves from certain or all directions are those with self-dual characteristics of their electric and magnetic responses. In this presentation we will present and discuss the general conditions for zero backscattering from arbitrary electrically small structures. Based on the general theoretical results, we will show that a small antenna composed of three orthogonal chiral particles can be designed so that this sensor has zero backscattering for plane-wave illumination coming from any direction. In addition, this sensor perfectly separates signals of two orthogonal circular polarizations. While the backscattering is zero for any incident polarization, one of them simply does not interact with this sensor, while the other polarization is effectively received.

8423-20, Session 5

Extremely thin metamaterial absorbers for subterahertz waves: from fundamentals towards applications in uncooled bolometric sensors

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The range of subterahertz electromagnetic waves (0.1-1 THz) remains an attractive area for applied sciences and technologies due to high penetrability of T-rays through various optically opaque materials and media, as well as attainability of a sufficient spatial resolution upon object imaging. When investigating objects, their data informativity can be noticeably increased if different spectral bands and polarization discrimination are involved in data processing. Such terahertz sensors or cameras, combining the options of high spatial resolution, multispectral capability, polarization sensitivity, low cost and real-time operation are commercially unavailable and remain much demanded.

In this contribution we introduce the concepts of micro-Golay cell arrays and THz-to-IR converters, as the flexible uncooled bolometric detectors with the aforementioned functional capabilities that were recently developed by our group for spectropolarimetric applications and imaging with CW terahertz oscillators. As the spectrally selective radiation-sensitive elements for such detectors we propose and investigate the high-performance ultra-thin metamaterial-inspired absorbers, which were designed for a narrow-band operation in the frequency range 0.1-0.4 THz at bandwidth selectivity ~5% and close to unity resonant absorptivity. The absorbers utilize a conventional high-impedance surface configuration ("FSS + grounded dielectric slab"), wherein a low-loss polypropylene film 15-20 um thick is employed as a grounded dielectric substrate, while a high-conductivity aluminium metallization is used in the "ground" plane and frequency selective surface (FSS) layers. Unlike the classical quarter-wave electromagnetic absorbers, this type of absorbing structures is estimated to have the high prospects for bolometric applications due to possibility for extreme minimization of the absorber thickness with respect to the operating free-space wavelength. Such minimization is essential for decreasing the absorber's heat capacity that allows achieving a high sensitivity and low response time of the bolometric sensor.

By appealing an equivalent circuit model analysis and 3D full-wave electromagnetic simulations in Ansoft HFSS software, the electromagnetic response of absorbers with different FSS cell geometries is thoroughly analyzed and fundamental relations between the resonant absorption bandwidth, wavelength-to-thickness ratio, FSS conductivity, dielectric slab loss tangent and other parameters, are established. Through the performed analysis we highlight the advantage of the chosen low-loss bulk materials (polypropylene and aluminium) to maximize the absorber's wavelength-to-thickness ratio. Limited by the lithographic fabrication technology, this ratio in our case was shown to attain the values ~50 for FSS with split-ring resonator elements, while reaching the record-breaking magnitudes ~180 for the case of a metallic patch array FSS. It is noteworthy that the results of electromagnetic modeling for such extremely thin absorbers appeared to be in a very good agreement with their experimental characterization by using a BWO-spectroscopy technique, which demonstrated 93-97% of the resonant absorptivity at the designed wavelengths. The developed absorbers were further effectively used for integration with T-ray sensing devices (matrix sensors), and we present the first results on single- and multi-spectral subterahertz BWO-imaging and spectropolarimetry using such detectors.

8423-21, Session 5

Dirac cone dispersions and metamaterials

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Dirac cone dispersions in the bandstructure in electronic and photonic system possess many remarkable transport properties. Metamaterials with a zero refractive index also possess very interesting wave manipulation characteristics. While these two classes of materials are apparently unrelated, they are actually linked together in classical wave systems in a subtle way. We show that by employing accidental degeneracy, dielectric photonic crystals can be designed and fabricated which exhibit Dirac cone dispersion at the center of the Brillouin zone at a finite frequency. Moreover, by applying effective medium theory, a subset of such dielectric photonic crystals can be mapped to a material with effectively zero permittivity and permeability and hence zero refractive index. A zero refractive index metamaterial is one in which waves do not experience any spatial phase change and such peculiar material has many interesting wave manipulating properties. We numerically and experimentally demonstrate in the microwave regime that such dielectric photonic crystals with reasonable dielectric constants do manipulate waves as if they have near zero refractive indices at and near the Dirac point frequency. Such materials may be useful for cloaking which in many cases require certain components of permittivity and permeability to be zero. Without introducing metallic resonant structure, this kind of dielectric photonic crystal based metamaterial will be applicable to various optical applications. The concept can also be extended to acoustic and elastic waves. For the case of elastic waves, we show that Dirac cone dispersion at the Brillion zone center can be related to a special kind of elastic crystal in which only longitudinal wave is allowed in certain directions and only transverse wave is allowed in some other directions. Effective medium theory finds that this phononic crystal has effectively zero mass density and zero effective 1/ C44 at the Dirac point.

8423-22, Session 5

Diffraction-managed superlensing using metallodielectric heterostructures

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Plasmonics discloses by means of a considerable number of evidences how to mold the flow of subwavelength wave fields. Proofs are found in extraordinary transmission of thin metallic films with holes and slits, and also in the generation and transport of ultra-localized hot spots in wired media, to mention a few. Those are suitable for applications in high-density waveguiding, biosensing and photovoltaics. Multilayered superlenses are also plasmonic heterostructures which are capable of reconstruct a given scattered wave field including subwavelength features. The main application of this sort of flat near-field lenses is high-resolution optical lithography.

The image formation in a single-layer metallic superlens is based on the excitation of surface plasmons polaritons and anti-plasmons on the entrance and exit interfaces, providing wave amplification to compensate the attenuation produced in the surrounding host medium. By coupling these elementary thin lenses we develop a device to deliver high-spatial-frequency harmonic waves by resonant tunneling. Assuming a periodic process, evanescent waves in bulk dielectric are effectively converted into propagating Bloch waves with characteristic propagation constant.

Two main factors are decisive in order to achieve an accurate replica of the scattered field. We are bound to prevent firstly resonant peaks in the transmittance response and secondly dephasing of different spectral components within the heterostructure. A plausible solution involves the use of metals and dielectrics of opposite permittivity together with balanced filling factors.

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In this contribution we analyze a different approach in order to control dephasing of subwavelength outputs. This is based on neutralization of the phase response in high-transparent metallic superlenses. A first hybrid stratified medium is in charge of transforming an evanescent wave into a Bloch wave field. A second metal-dielectric multilayer manages diffraction-induced divergence by means of negative refraction. As a consequence, an ultra-flattened spectral phase of the signal at the exit interface leads to a subwavelength point spread function of the coupled imaging setup.

8423-23, Session 5

Subwavelength diffraction-free beams in metallic wire media

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Bessel beams are wave fields traveling in free space that are characterized by a prescribed propagation constant along a given direction and concurrently their transverse pattern are clearly localized around the focus [1]. Since intensity has cylindrical symmetry despite of diffraction effects, soon they were coined diffraction-free beam. However, the Bessel beamsize is unambiguously limited by diffraction inasmuch as its FWHM is greater than half the wavelength.

Transferring such ideas to optically structured media is strikingly easy to do but still barely unexplored [2]. Head attention has been deviated to guided modes for long due to its key role in telecommunications systems. Since the host medium cannot confine nondiffracting beams by definition, they may be interpreted as a tight focusing within bulk inhomogeneous media. Potential applications include femtosecond laser submicrochannel machining and optical trapping and guiding of micro- and nano-size objects.

Not long since we theoretically confirmed that a metal-dielectric stratified medium may sustain diffraction-free beams, even including losses in the plasma [3,4]. In particular, the existence of Bessel plasmons deserves special attention [5]. Grazing propagation confirms that such a behavior is not sustained by canalization but depends on the waveform itself. Additionally, the assistance of surface plasmons polaritons (SPPs) leads to subwavelength beamsizes. Here we present recent progress in nondiffracting subwavelength fields circulating in complex plasmonic nanostructures. In particular, localized diffraction-free SPPs in a wired medium are discussed thoroughly.

[1] J. Durnin, J.J. Miceli, and J.H. Eberly, “Diffraction-free beams,” Phys. Rev. Lett. 58, 1499-1501 (1987).

[2] O. Manela, M. Segev, and D. N. Christodoulides, “Nondiffracting beams in periodic media,” Opt. Lett. 30, 2611-2613 (2005).

[3] J.J. Miret and C.J. Zapata-Rodríguez, “Diffraction-free propagation of subwavelength light beams in layered media,” J. Opt. Soc. Am. B 27, 1435-1445 (2010).

[4] J.J. Miret, D. Pastor, and C.J. Zapata-Rodríguez, “Subwavelength surface waves with zero diffraction,” J. Nanophoton. 5, 051801 (2011).

[5] C.J. Zapata-Rodríguez, S. Vukovi, M.R. Beli, D. Pastor, and J.J. Miret, “Nondiffracting Bessel plasmons,” Opt. Express 19, 19572-19581 (2011).

8423-24, Session 6

Tunable microwave metamaterials controlled by light

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We propose a novel approach for creating tunable electromagnetic metamaterials. We demonstrate experimentally that the magnetic resonance of a split-ring resonator (“meta-atom” of the metamaterial) with a photodiode operating in a photovoltaic mode can be tuned by changing the intensity of an external light source. For two coupled resonators we show that we can achieve light-induced switching between dark and bright mode response. By illuminating individual meta-atoms with different light intensity it will become possible to create dynamically reconfigurable spatially-inhomogeneous structures, such as graded index lenses, prisms, mirrors, etc. We build a simple microwave metamaterials composed of the light-controlled split-ring resonators and demonstrate several functionalities of these novel metamaterials: light-tunable microwave mirror and light-induced microwave (convex or concave) lenses We believe this approach can be useful for creating novel metamaterial devices whose properties are controlled entirely by incident light.

8423-25, Session 6

Switching nonlinearity in a superconductor-enhanced metamaterial

S. M. Anlage, Univ. of Maryland, College Park (United States)

A recent trend in the field of electromagnetic metamaterials is the development of artificial materials with tunable or nonlinear properties. We demonstrate a nonlinear metamaterial that can be switched between low and high transmission by controlling the power level of the incident beam. The origin of this nonlinear response is the superconducting Nb thin film employed in the metamaterial structure demonstrating a classical optical phenomenon analogous to electromagnetically induced transparency [1,2]. The two-dimensional design employs two planar Nb split rings acting as dark resonators symmetrically placed around a thick Au strip acting as a bright resonator. When Nb is in the superconducting state, the significant loss gradient between Nb and Au opens a transparency window along with a strongly enhanced group delay. We show that with moderate RF power of about 22 dBm it is possible to quench the superconducting state as a result of extremely strong current densities at the corners of the metamolecule’s split-ring resonators [3]. We measure a transmission contrast of 10 dB and a change in group delay of 70 ns between the low and high input power states.

[1] L. Zhang, Philippe Tassin, Thomas Koschny, Cihan Kurter, Steven M. Anlage, and C. M. Soukoulis, Large group delay in a microwave metamaterial analogue of electromagnetically induced transparency. Appl. Phys. Lett. vol. 97, 241904, 2010.

[2] Cihan Kurter, Philippe Tassin, Lei Zhang, Thomas Koschny, Alexander P. Zhuravel, Alexey V. Ustinov, Steven M. Anlage, and Costas M. Soukoulis, Classical Analogue of Electromagnetically Induced Transparency with a Metal/Superconductor Hybrid Metamaterial, Phys. Rev. Lett. vol. 107, 043901 (2011).

[3] Cihan Kurter, Philippe Tassin, Alexander P. Zhuravel, Lei Zhang, Thomas Koschny, Alexey V. Ustinov, Costas M. Soukoulis, Steven M. Anlage, Switching Nonlinearity in a Superconductor-Enhanced Metamaterial, arXiv:1110.5677.

8423-26, Session 6

Thermally and optically tunable high-temperature superconducting terahertz metamaterials

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Through the integration of semiconducting or ferroelectric materials into the metallic resonators, tunable metamaterials have been achieved by a change of environment using an external stimulus. Metals provide high conductivity to realize a strong resonant response in the structures; however, they contribute very little to the tunability in metamaterials. The complex conductivity in high-temperature superconducting films is highly sensitive to external perturbations, which provides new opportunities in achieving tunable metamaterials resulting directly from the resonant elements. Recently we experimentally demonstrated thermally and optically tunable planar terahertz (THz) metamaterials, where the metal resonators are replaced with high-temperature superconducting resonators, i.e. YBCO split-ring resonators (SRRs). The superconducting Cooper pairs are broken to quasiparticle state by increasing temperature or application of near-infrared femtosecond laser pulses, which dramatically modify the imaginary part of the complex conductivity and consequently the metamaterial resonance. We observed the resonance switching accompanied with an interesting frequency tuning as a function of temperature or photoexcitation fluence, which also strongly depend on the thickness of the superconducting films. We carried out finite-element numerical simulations using the experimentally measured values of the complex conductivity of the superconducting films at various temperatures and photoexcitation fluences, which nicely reproduced the experimental observations. We further developed an analytical model that explains the tuning features of the metamaterial resonance, which takes into account the impacts of both the resistive damping and additional kinetic inductance contributed from both the real and imaginary parts of the complex conductivity in YBCO films. The theoretical calculations reveal that the increasing SRR resistance upon increasing temperature or photoexcitation fluence is responsible for the reduction of the resonance strength, and both the resistance and kinetic inductance contribute to the tuning of the resonance frequency.

8423-27, Session 6

Electrically tunable mid-infrared metamaterials

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There has been tremendous interest in the development of optical metamaterials. Artificially tailored electromagnetic structures can exhibit exotic optical properties such as optical magnetism, negative refraction, sub-diffraction imaging, and cloaking. Active tuning of metamaterials is emerging as a natural next step in this burgeoning field. Tunable metamaterials also have potential for novel active devices such as optical switches, modulators, filters, and phase shifters. There have been several approaches for active tuning - e.g. with mechanical movement or stretching, reorientation in liquid crystals, and phase transitions in vanadium dioxide. However, electrical control based on semiconductor device structures is more technologically appealing for practical, chip-scale devices. In this talk, we present electrically-controlled active tuning of mid-infrared metamaterials using depletion-type devices. The depletion width in an n-doped semiconductor epilayer changes with an electric bias, inducing a change of the permittivity of the substrate and leading to frequency tuning of the resonance. We first discuss our detailed theoretical analysis and then present experimental data of bias-dependent metamaterial transmission spectra. We also think of possible ways to increase tunability further. The mid-IR spectral range is technologically important for a number of applications, including chemical/biological sensing, thermal imaging, and free-space optical communication. Thus, we expect that this electrical tuning of metamaterials find important applications in chip-scale active infrared devices.

8423-10, Session 7

Polarization scrambling with meander structures

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We demonstrate strong optical activity without chirality of periodic meander-type plasmonic metamaterials. Meander-type metamaterials are therefore perfect candidates for polarization scramblers among many other applications. This holds especially for space devices, which would benefit from the radiation stability, temperature independence, low weight, large-scale manufacturability and high polarization rotation power of such metamaterial structures.

We clarify that the metallic meander [1] is one of the most suited plasmonic structures for this purpose. Firstly, the meander structure not only represents a linear polarizer but also a phase-retarder. In particular it manifests large optical activity, which is induced by the polarization-sensitive excitation of resonant plasmon modes [2]. All these properties combined lead to a Müller-Matrix, of which the elements are dependent on the incident and azimuth angles. To obtain a depolarizing effect for arbitrary polarized light, including circularly polarized light, we show that the relevant elements of the Müller-Matrix can be averaged out or become zero. We investigate the structure with different simulation tools and find that the retrieved Müller-Matrices fit our predictions well.

With these findings, we propose a polarization scrambler consisting of one-dimensional meander structures that are distributed on the substrate in a pixel-like fashion. Each pixel of the array has a random angular orientation so that any arbitrarily polarized light beam incident on such a device with a certain amount of pixels can be depolarized.

[1] L. Fu, H. Schweizer, T. Weiss, and H. Giessen, Journal of the Optical Society of America B 26(12), B111 (2009).

[2] S. Zhukovsky, A. Novitsky, and V. Galynsky, Opt. Lett. 34, 1988 (2009).

8423-28, Session 7

Control of resonance characteristics of metamaterials in THz and optical frequency range

J. Wu, Ewha Womans Univ. (Korea, Republic of)

Electromagnetic induced transparency is an example of Fano resonance where a coherent coupling between high and low Q-factor resonances gives rise to a transparency window in the low Q-factor resonance absorption. One advantage of metamaterial is that the resonance feature can be controlled by designing the geometric shape of constituent metaparticles. In order to control EIT by the polarization direction of incident electromagnetic wave, two different kinds of metamaterials are introduced. One is a superlattice metamaterial, and the other is an isotropic metamaterial. The superlattice metamaterial accommodates two distinct metaresonances, the magnitude and Q-factor of which is dependent on the polarization direction. When the superlattice metamaterial and the isotropic metamaterial are superimposed, a coherent coupling gives rise to a polarization-dependent Fano resonance. Another example of resonance control is to introduce the Babinet principle in designing the metamaterial. By comparing the resonance characteristics of metamaterial patterns fabricated by the e-beam lithography lift-off and the focused ion beam milling, polarization-angle dependent meta-resonances are investigated.

8423-29, Session 7

Plasmonic nanojets: ultrafast hydrodynamics in metamaterials

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When a pebble drops on the surface of water, it is often observed that a water column, or "back-jet", surges upwards. Counter-intuitive though it might be, a similar phenomenon can occur when light shines on a metal film surface. Indeed, tightly focused femtosecond laser pulses carry sufficient energy to locally melt the surface of a gold film and the impact from these laser pulses produces a nanojet, as has been theoretically described and experimentally demonstrated. In particular, these studies show that the very fast cooling rate of the nanojet, allows it to "freeze" in shape, as the temperature drops below the melting point. The gold surface can therefore be imprinted with nanostructures, each marking the point of impact of a laser pulse. Moreover, just as in the case of water, nanojets can result in the projection of a small droplet.

We demonstrate that, in planar arrays of plasmonic nanostructures, the laser intensity can be tuned so that melting occurs only in the hotspots, leaving the rest of the nanostructure unaffected. Consequently, the hydrodynamic processes leading to nanojets and nanobumps occur only in the plasmonic hotspots. This insight into the basic interactions of light and materials at the nanoscale opens up new possibilities for studies and applications.

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8423-30, Session 7

Plasmonics: from quantum effects to Fano interference and light harvesting

P. J. Nordlander, Rice Univ. (United States)

The "plasmon hybridization"concept,[1] shows that the plasmon resonances in complex metallic nanostructures interact and hybridize in an analogous manner as atomic wavefunctions in molecules. This insight gained from this concept provides an important conceptual foundation for the development of new plasmonic structures that can serve as substrates for surface enhanced spectroscopies, chemical and biosensing, and subwavelength plasmonic waveguiding and other applications. The talk will focus on a few recent "hot topics" such as plasmonic Fano resonances,[2] quantum plasmonics and plexcitonics,[3] and active plasmonic nanoantennas for enhanced light harvesting,[4] and plasmon induced chemical reactions.[5]

[1] N.J. Halas et al., Chem. Rev. 111(2011)3913

[2] B. Lukyanchuk et al., Nature Mat. 9(2010)707; S.P. Zhang et al., Nano Lett. 11(2011)1657; P. Alonzo-Gonzalez et al., Nano Lett. 11(2011)3922; Z.Y. Fang et al., Nano Lett. 11(2011)4475; J.A. Fan et al., Nano Lett. 11(2011)10.1021/nl203194m

[3] J. Zuloaga et al., Nano Lett. 9(2009)887; ACS Nano 4(2010)5269 ; P. Song et al., J. Chem. Phys. 114(2011)074701; A. Manjavacas et al., Nano Lett. 11(2011)2318

[4] M. W. Knight et al., Science 332(2011)702

[5] R. Huschka et al., J. Am. Chem. Soc. 133(2011)12247

8423-31, Session 7

Plasmonic Brewster angle for broadband absorption, enhanced nonlinearities and directional emitters

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Following our recent results on ultrabroadband enhanced optical transmission through a plasmonic grating at the 'plasmonic Brewster angle', we propose here some exciting applications and extensions of this concept to realize planar, quasi-isotropic broadband absorbers, directional emitters and metamaterials with enhanced nonlinear properties. The anomalous matching phenomenon that characterizes plasmonic grating with ultrathin slits at its Brewster transmission is very distinct from conventional extraordinary optical transmission. It is based on an anomalous matching at the interface between the grating and free-space [Phys. Rev. Lett. 106, 123902 (2011)], rather than relying on resonant phenomena. This property makes the phenomenon very robust to the addition of absorption in the grating, suggesting that ultrabroadband, thin planar absorbers may be realized based on similar concepts. In addition, proper patterning of the grating may provide two-dimensional, quasi-isotropic functionality on the plane, although the absorption mechanism remains polarization sensitive. As an additional interesting property, the large field enhancement in the slits may also be employed for interesting effects in nonlinear optics, producing broadband boosting of optical nonlinearities with much lower Q factors than in conventional Purcell effects. This concept may be employed for harmonic generation and nonlinear hysteresis over broad bandwidths. Finally, similar concepts may be applied to realize novel energy-harvesting devices. It is predicted that such systems may realize very efficient, ultrabroadband directional emitters, spanning a large portion of the infrared spectrum, for exciting applications in thermophotovoltaic systems. We will discuss these concepts and optimized designs during our talk.

8423-32, Session 8

Passive plasmonic components based on sub-wavelength structured metal film

T. J. Cui, X. Shen, Southeast Univ. (China)

Metamaterials have attracted great attentions due to their many interesting properties. They are artificial materials with subwavelength unit cells that can be designed to manipulate the propagation of electromagnetic waves in a new manner different from that in nature materials. Highly confined spoof surface plasmon polaritons (SPPs) can be efficiently guided to propagate along planar structured metamaterials with low propagation loss and bending loss. In this talk, we report the analysis, design, fabrication, and measurements of plasmonic metamaterial components, such as bend, power divider, ring resonator, and directional coupler, based on the structured metal surfaces. The experiment results agree very well to the full-wave simulations. Such plasmonic metamaterial components are subwavelength scales and have prospective implementations in highly integrated plasmonic circuits.

8423-33, Session 8

Conquering loss in metamaterials and plasmonics: from optical gain to parametric amplification

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Optical loss in metal is a known problem hindering many applications of plasmonics and metamaterials. A common solution to the loss problem is addition of optical gain to a dielectric adjacent to metal. However, population inversion is an unavoidable source of a spontaneous emission noise, which may be as harmful to applications as loss. Parametric amplification in nonlinear media may present an alternative solution to the problem. In this presentation, we will review our studies of plasmonic and metamaterial systems with optical gain as well as the first steps toward nonlinear parametric amplification of surface plasmons.

8423-34, Session 8

Plasmonic nanoparticles assemblies: preparation, structural, and optical properties

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Our goal is the preparation of metamaterials in the visible spectral range using self-assembly routes. Such an approach is based on the coupling of plasmons of individual nanoparticles within larger structures. We report on our experimental attempts for the realization of such structures using different strategies involving the use of surfactants to form nanoparticle composites or the use of dielectric beads and the assembly of metal nanoparticles at its surface (core-shell structures). We furthermore fabricated systems where nanoparticles were assembled in arrays on a flat substrate by a layer-by-layer deposition using poly-electrolytes in order to exploit coupling between particles in different arrays. The experimentally determined structure and optical response of the assemblies were used to derive adequate model systems that allowed the simulation of the spectral response and extraction of optical properties.

Gold nanoparticle arrays were prepared on glass substrates using layer-by-layer self-assembly by first depositing negatively charged gold nanoparticles on a positively charged substrate. On top of that first gold nanoparticle layer polyelectrolyte multilayers were adsorbed followed by a second gold nanoparticle array. The change observed in the spectral profile of the layer upon the introduction of a second nanoparticle array depends upon the size of the nanoparticles, their separation, and the polarization and direction of the incoming radiation. The necessary control of spacing can be achieved through the build-up of individual polyelectrolyte (PE) layers in-between the gold nanoparticle arrays in an extensively studied process known as layer-by-layer assembly. Here, the separation between the arrays of gold nanoparticles depends solely on the number of polymer layers used. The electrostatic attraction between the oppositely charged polymers and the introduction of negatively charged gold NPs gives rise to a highly flexible system with a large degree of control over a wide variety of parameters, almost to within nanometer precision. Using similar assembly techniques core-shell structures can also be prepared using silica spheres as templates. These structures are shown to support dominant magnetic resonances.

8423-35, Session 8

Angle-resolved cathodoluminescence imaging spectroscopy of plasmonic metamaterials

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We present a novel technique, Angle-Resolved Cathodoluminescence Imaging Spectroscopy (ARCIS), that enables, for the first time, measurements of both the local optical density of states and modal dispersion of nanophotonic structures at deep subwavelength resolution.

The ARCIS instrument is composed of a 30 keV field-emission SEM with a half-parabolic mirror integrated between the microscope's pole piece and the sample. Light is collected and spectrally analyzed to determine the spatial-resolved DOS, and, in a parallel geometry, directed onto a 1024x1024 pixel CCD array that images the beam profile emanating from the mirror. Using this Fourier imaging geometry, the angle-resolved emission pattern can be determined at an angular resolution of 1 degree, over a solid angle as large as 1.4 sr. (NA=0.99). With the SEM in high-resolution mode, the spatial resolution of the ARCIS technique is as small as 1-10 nm. The collected photon count rate over the 400-950 nm spectral band is between 10 and 100 million counts/sec, depending on the sample and the beam current.

The ARCIS technique is a unique tool to characterize photonic structures in which the local DOS varies on a subwavelength scale, and is thus ideally suited for studies in plasmonics and metamaterials. Such studies cannot be made using conventional microscopy due to the limitations imposed by the diffraction limit. The ARCIS technique also surpasses the resolution of conventional near-field microscopy, with the added advantage that the geometry under study is not affected by a fiber probe. When applied on optically doped nanomaterials such as e.g. rare earth doped geometries, the ARCIS geometry can also be used for spatially and angle-resolved fluorescence lifetime imaging.

In this presentation, we give detailed insight in the design of the ARCIS system and its measurement characteristics. We will present several successful applications of the technique to obtain insight in the photonic density of states and radiation profiles for metal nanoparticles, nanoparticle dimers, Yagi Uda antennas, metal nanorod antennas, planar elliptical plasmonic antenna's, and epsilon-near-zero materials.

8423-94, Session 8

Alternative route to low-loss metamaterials and plasmonics

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Metamaterials are a class of artificial materials designed to interact with light in ways no natural materials can.

The exotic and often dramatic physics demonstrated by the metamaterials is generally underpinned by the light-scattering properties of sub-wavelength metallic resonators (metamolecules) that form metamaterials.

Due to its resonant nature the response of the metamaterials is very sensitive to the presence of losses in the constituting metals. The losses are particularly strong in the plasmonic regime (i.e. at optical frequencies) hampering the use of metamaterials for photonic applications.
The list of mainstream solutions considered at present includes, in particular, the search for better plasmonic media among metallic alloys, semiconductors and conductive oxides, as well as direct compensation of losses by combining metamaterials with various optical gain media or use of superconductors. Here we present an alternative solution, which enables significant reduction of plasmonic losses at the metamaterial fabrication stage and is based on structure engineering of conventional plasmonic materials.

8423-36, Session 9

Non-Foster particles for metamaterials

N. Engheta, Univ. of Pennsylvania (United States)

Non-Foster circuits in radio-frequency (RF) electronics have been a class of circuits in which the negative impedance converter is used and as a result the input impedances of such circuits do not follow the Foster reactance theorem. Over the years these circuits have been used for various applications such as the antenna matching. In my group, we have been exploring the possibility of having particles and structures that exhibit the analogous non-Foster features, as possible inclusions for non-Foster metamaterials. In such structures and particles two signals can be mixed, i.e., the input signal with frequency omega with the input pump with frequency of 2*omega, resulting in the variation of the effective linear permittivity due to the proper levels of nonlinearity and pump intensity. In this talk, we will discuss our theoretical results for such non-Foster particles and structures.

8423-37, Session 9

Hybrid quantum dot-metal nanoparticle systems: connecting the dots

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Hybrid molecules formed by coupling semiconductor quantum dots (SQD) to metal nanoparticle (MNP) nanoantennas provide a new paradigm for directed nanoscale transfer of quantum information and new building blocks to exploit in making metamaterials. To assess these possibilities, we study theoretically the response of these hybrid molecules to applied optical fields. Quantum-coherent time-evolution of the SQDs in the hybrid molecule is found by solving the SQD density matrix equations. We study hybrid molecules in the weak and strong coupling regimes. In strongly driven, strongly dipole-coupled SQD-MNP hybrids with spherical MNPs, interference, dispersion near resonance and self interaction define the MNP/SQD coupling and lead to Fano resonances, exciton induced transparency, suppressed SQD response and bistability. More complicated response can be tailored by using MNP shape and the placement of SQDs to control the local near-fields that couple the MNPs and SQDs. We describe how coupling to MNP dark modes and higher order multipolar modes impact interference and self-interaction effects. The physics of the MNP/SQD coupling is outlined and its impact on the optics of these structures is discussed.

8423-38, Session 9

Optical spectroscopy, cathodoluminescence, and electron energy loss spectroscopy on metal nanoparticles

V. Myroshnychenko, J. F. García de Abajo, Instituto de Química-Física (Spain)

The current tremendous interest in the optical properties of metal nanoparticles is due to their ability to host localized surface plasmon excitations in the visible and near-infrared parts of the spectrum, which are important for applications to telecoms and other technologies and constitute the basic building blocks of metamaterials. Plasmons can be tailored via the size and morphology of metal nanoparticles. This has given rise to an active field of research aimed at finding new recipes for controlling their size and shape. All of these enable a wide range of applications in areas such as switching, light guiding, optical trapping, and bio-sensing. Knowledge and experimental access to the electromagnetic field distributions associated to localized plasmon excitations in metal nanoparticles, with high degree of energy and spatial resolution, are of critical importance in the development of these applications.

Here, we review the use of optical spectroscopy, electron-induced radiation emission (cathodoluminescence), and electron energy-loss spectroscopy to study localized surface plasmon excitations in sub-wavelength noble-metal nanoparticles prepared via lithography or colloidal chemistry. These techniques provide information about plasmon excitations by recording different physical processes, specifically, light scattering exerted by the particles on externally incoming light, radiation emission produced by interaction with an electron beam, and energy loss suffered by those electrons. We provide a theoretical description of a study of the spectral features and spatially resolved maps of nanoparticle plasmon modes at the single-particle level by using these techniques. We discuss the similarities and differences between these techniques as well as a comparative analysis of the information that they provide. Numerical modeling is carried out for each set of experimental measurements in order to interpret the results and understand the nature of the excited plasmon modes. Our comparative assessment of the experimental techniques used in this work demonstrates an extremely high capability of electron energy-loss spectroscopy and cathodoluminescence in resolving and imaging surface plasmons in small subwavelength metal nanoparticles with unrivalled spatial and energy resolution.

8423-39, Session 9

Cloaking dielectric spheres by a shell of plasmonic nanoparticles

M. D. Farhat, S. Muehlig, C. Rockstuhl, F. Lederer, Friedrich-Schiller-Univ. Jena (Germany); A. Cunningham, T. Buergi, Univ. of Geneva (Switzerland)

We describe in this contribution a metamaterial made of an amorphous arrangement of silver nanospheres covering a dielectric sphere with the objective to make it undetectable by exterior observers. This structure is studied rigorously by full wave simulation and approximately by treating the shell of silver nanoparticles within the effective field theory (Maxwell-Garnett approximation). By both methods it is clearly shown that such a metamaterial shell significantly reduces the visibility of the dielectric sphere by annihilating its electric dipole moment (in the quasistatic limit).

In this work, we build upon the work of Alù et al. [Phys. Rev. E 2005 72, 016623 (2005)] who proposed a cloaking technique based on scattering cancelation which consists of coating the object to be cloaked by plasmonic layers to cancel the total scattered field, and we further suggest to use a bottom-up metamaterial designing of such cloak instead of homogenous plasmonic layers. The advantages of our approach are: i) a possibly better tunability that avoids metallic shells with minuscule thicknesses, ii) a more efficient cloaking reduction at higher frequencies, and iii) a back-up of a wide range of technologies for its implementation based on colloidal nanochemistry. Our study contributes to pave the way to consider metamaterials in the design process of functional devices. Thus, it will be shown that in the plasmon resonance of the particles deviating results are encountered whereas at the operational frequency of the cloak, which is off-resonant, predictions by both methods perfectly agree and more than 70% of scattering reduction is achieved. Moreover, we are working on the implementation of our cloak in an optical experiment where bottom-up methods from colloidal nanochemistry are used to decorate a dielectric sphere by sufficiently densely packed small metallic nanoparticles (silver in our case).

8423-40, Session 9

Cloaking in layered system of nanosphere-dispersed nematic liquid crystal metamaterial for chosen infrared wavelengths

G. Pawlik, A. Mitus, Wroclaw Univ. of Technology (Poland); I. Khoo, The Pennsylvania State Univ. (United States)

Recently [1,2], we have discussed a design of an infrared cylindrical cloak using nanosphere dispersed nematic liquid crystal metamaterial [3]. Cloaking conditions require spatial distribution of liquid crystal birefringence with constant extraordinary index and radially dependent ordinary index of refraction. In the experimental realization the calculated radial distribution of ordinary index, can be approximated by a stepwise distribution and implemented using cylindrical NLC layers separated by IR transparent walls.The present study is focused on numerical optimization procedures for maximization of cloaking effects in layered device.

[1] G. Pawlik, W. Salejda, K. Tarnowski, W. Walasik, A. C. Mitus, and I.C. Khoo, Proc. SPIE. 8114, 81140G (2011).

[2] G. Pawlik, W. Salejda, K. Tarnowski, W. Walasik, A. C. Mitus, and I.C. Khoo, submitted to Opt. Lett. (2011).

[1] I.C. Khoo, D.H. Werner, X. Liang, A. Diaz, and B. Weiner, Opt. Lett. 31, 2592 (2006).

8423-41, Session 9

Optical pulse frequency conversion inside transformation-optical metamaterials

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Based on the analogy between the Maxwell equations in complex metamaterials and the free-space Maxwell equations on the background of an arbitrary metric, transformation optics allows for the design of metamaterial devices using a geometrical perspective. This intuitive geometrical approach has already generated various novel applications within the fields of invisibility cloaking, electromagnetic beam manipulation, optical information storage, and imaging. Nevertheless, the framework of transformation optics is not limited to three-dimensional transformations and can be extended to four-dimensional metrics, which allow for the implementation of metrics that occur in general relativistic or cosmological models. This enables, for example, the implementation of black hole phenomena and space-time cloaks inside dielectrics with exotic material parameters.

In this contribution, we present a time-dependent metamaterial device that mimics the cosmological redshift. Theoretically, the transformation-optical analogy requires an infinite medium with a permittivity and a permeability that vary monotonically as a function of time. We demonstrate that the cosmological frequency shift can also be reproduced in more realistic devices, considering the fact that practical devices have a finite extent and bounded material parameters.

Indeed, our recent numerical results indicate that it is possible to alter the frequency of optical pulses in a medium with solely a modulated permittivity. Furthermore, it is shown that the overall frequency shift does not depend on the actual variation of the permittivity. The performance of a finite frequency converter is, for example, not affected by introducing the saw tooth evolution of the material parameters. Finally, we studied the effect of the introduction of realistic metamaterial losses and, surprisingly, we found a very high robustness with respect to this parameter. These results open up the possibility to fabricate this frequency converting device with currently available metamaterials.

8423-59, Poster Session

Unidirectional transmission in photonic-crystal gratings at beam-type illumination

A. O. Cakmak, E. Colak, Bilkent Univ. (Turkey); A. E. Serebryannikov, Technische Univ. Hamburg-Harburg (Germany); E. Ozbay, Bilkent Univ. (Turkey)

In the limiting case of the directional selectivity such a device that would allow (nearly) total transmission in one direction and no transmission in the opposite direction within the same propagation channel could be considered as the electromagnetic counterpart of a diode. The conventional approach to achieve the unidirectional transmission in passive devices is based on the use of the anisotropic or nonlinear materials. In particular, the strongly pronounced unidirectional transmission has been demonstrated for the one-dimensional photonic crystals (PCs) and for the stacks of the two-dimensional PCs, in which anisotropic materials were utilized. Directional waveguides have been realized in PCs with broken time-reversal symmetry.

In this paper, we investigate the directional selectivity in the PC gratings in the microwave regime at beam-type illumination. The simulations and the microwave experiments are performed for a wide frequency range that involves the first five PC bands (Floquet-Bloch waves), which are distinguished in terms of their respective dispersion features. The presented results include the transmission spectra of the examined structures for the plane-wave illumination, the frequency response of the transmittance for Gaussian-beam and horn antenna illuminations, and the angular distributions of the transmittance, at a proper value of the angle of incidence.

In this work, we have demonstrated unidirectional transmission in the PC gratings with one-side echelette-type corrugations at beam-type illumination. Simulation results obtained for the plane-wave and Gaussian-beam illuminations, and the experimental results for the microwave horn antenna illumination were presented and analyzed. We have observed a good connection between the features detected at plane-wave, Gaussian-beam and horn antenna illuminations.

8423-60, Poster Session

Strong magnetism by closely spaced gold nanohoops

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It has been shown that engineered metallic nanoparticles can strongly respond to the magnetic field of an incoming optical wave. Ultimately this magnetic response can lead to an effective permeability different from 1 at optical frequencies, which could give rise to optical metamaterials with special properties such as negative index of refraction of cloaking. Typically, the magnetic response is achieved from a couple of horizontal nanoplates put in close proximity, as in the case of the so-called fishnet metamaterial.

In this work, we show that closely-spaced gold nanohoops can provide a strong magnetic response in the near infrared regime. Therefore, a single metallic layer is needed to achieve the magnetic performance. A key point to achieve this response is that the aspect ratio (defined as the ratio between the metal thickness and the nanohoop spacing) must be higher than 1. To fabricate such structures, electron-beam lithography is utilized to realize corresponding patterns with controlled radius and spacing in PMMA resist. Following with gold electroplating, high aspect-ratio gold nanohoops can thus be obtained with tunable thickness by modifying the plating time. Following with gold electroplating, gold nanohoops can thus be obtained with tunable thickness by modifying the plating time. In the fabricated samples, the external radius was 325 nm, the gold thickness was 275 nm, the spacing was about 150 nm and the hole radius was changed between 0 and 200 nm. Transmission and reflection spectra taken by use of a Fourier-Transform Infrared spectrometer show a strong absorbance peak at a wavelength that can be tuned by modifying the hole radius of the nanohoops and the dielectric substrate. Numerical simulations show that at the resonance wavelength a virtual current loop is created between adjacent nanohoops, giving rise to a large magnetic moment together with a strong magnetic field strength.

8423-61, Poster Session

Dispersion, diffraction, and surface waves in semi-infinite metal-dielectric superlattices

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We investigate dispersion and diffraction properties of periodic layered metal-dielectric nanostructures in the case when the thickness of a metal layer becomes comparable to, or smaller than metal's skin depth. Then, electromagnetic field properties in such a nanostructure can be dramatically affected by a nonlocal optical response and coupling of surface plasmon polaritons at different metal-dielectric interfaces. We demonstrate that the use of the so called "effective medium approximation", as a conventional approach for describing optical properties of the layered structures, and their description as uniaxial metamaterials (plasmonic crystals) is not justified, in general. However, there are narrow ranges of parameters where the "effective medium approximation" can be used. In particular, we study transitions through "epsilon-near-zero" and "epsilon-very-large" regimes, and compare the results obtained via effective medium model with the solutions of exact dispersion equations, including the influence of metallic losses. We demonstrate that, in the certain range of frequencies and layer thicknesses, taking into account non-localities leads to an additional extraordinary wave of TM polarization. Thus, instead of usual birefringence in uniaxial crystals we now may have tri-refringence: one TE-polarized and two TM-polarized waves. We show that those two TM-polarized waves may have different signs of the group velocities and diffraction.

To study surface wave propagation, we confine ourselves here, to the case when the effective-medium approximation is valid and the superlattice behaves like a uniaxial plasmonic crystal with the main optical axes perpendicular to the metal-dielectric interfaces. We demonstrate that if such a semi-infinite plasmonic crystal is cut normally to the layer interfaces and brought into the contact with semi-infinite dielectric, a new type of surface modes can appear. The propagation of such modes obliquely to the optical axes occurs under favorable conditions that regard thicknesses of the layers, as well as the proper choice of dielectric permittivity of the constituent materials. These modes are not polaritons, like surface plasmons, as all three components of the electric, as well as the magnetic field are involved. Thus, they are hybrid surface modes. We show that losses within the metallic layers can be substantially reduced by making the layers sufficiently thin. At the same time, a dramatic enlargement of the range of angles for oblique propagation of the new surface modes is observed.

8423-62, Poster Session

Analytic design of chirped planar photonic crystals in the metamaterial regime

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Controlling light paths and beam profiles of guided waves in planar optical structures has received a strong interest for some years. The main proposed approach relies on the use of metamaterials. Coupled with the formalism of transformation optics, this approach has led to several works showing the possibility to mold the flow of electromagnetic waves in almost arbitrary shape waveguiding structures. However, strongly anisotropic metamaterials with complicated permittivities and permeabilities are needed at optical frequencies, while strong losses are induced by the use of metals. For these reasons, experimental results have been mostly obtained by reducing the goal to the use of broadband all-dielectric structures, i.e. by relying on sub-wavelength dielectric structures to control the local average refractive index of planar optical waveguides.

We propose here to pursue a similar approach by developing an analytical method for the study of two-dimensional sub-wavelength structures. Relationships are given to predict the optical index map and air-hole drilling distribution required to make light follow a prescribed path. The method is applied to proof-of-concept structures based on the silicon-on-insulator technology. Light propagation is studied using Finite Difference Time Domain simulation to verify light trajectories, study the influence of extended light beams, and evaluate the robustness of the semi-classical approach based on the equations of Hamiltonian optics. The overall approach can be used for the design of optical functionalities within the so-called photonic sub-wavelength regime.

8423-63, Poster Session

Dynamics of frequency-modulated wave packets in nonlinear oppositely directed coupler

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In the present work the pulse dynamics of forward and backward waves in a planar structure comprising tunnel-coupled waveguides made from the positive (PIMs) and negative (NIMs) index materials will be described in approximation of the coupled waves. In contrast to the previous studies, our analysis will take into account radiation absorption in a structure, dispersive and nonlinear effects. Besides, utilization of such structures as slow light systems with the parameters controlled by the external magnetic field will be under discussion.

Herein, we will study the dynamics of the forward and backward waves in an absorbing NIM-PIM tunnel-coupled structure. The state of the NIM corresponds to the frequency range where the real part of the refractive index is negative. In this range, the effective reflection of the forward wave occurs as the phase-matching conditions are satisfied. We will show the ways to control the structure reflectivity by the external magnetic field employing its effect on the wave tunnel coupling and interaction length of the counter-propagating waves. In this case, the effective parameters, which define the pulse dynamics of the forward wave in such structures, are strongly dependent on characteristics of the input radiation (intensity, duration, rate of frequency modulation (chirp)). In the case of initial frequency modulation different from zero and sufficiently high effective dispersion, the velocity of the pulse envelope maximum propagates in the structure with acceleration (deceleration). Besides, in this tunnel-coupled structure, one can efficiently control the envelope maximum velocity of the wave packet, for example its significant slowing. The strong dependence of the effective parameters on the detuning from phase-matching makes these wave-structures promising for various radiation control systems. Moreover, the use of active laser materials with the PIM waveguide would enable light amplification compensating high light losses in NIM waveguide associated with high metamaterial absorption in the frequency range, where $n<0$.

8423-64, Poster Session

Dual hyperbolic-elliptic media

C. J. Zapata-Rodriguez, P. Cencillo, M. Avellaneda, Univ. de València (Spain); S. Vukovic, Univ. of Belgrade (Serbia); J. J. Miret, Univ. de Alicante (Spain)

Metal-dielectric superlattices are versatile metamaterials with unique dispersion properties. Recent advances in the fabrication of nanolayered devices have made possible to surpass the limit of the metal skin depth in the visible regime [1]. By means of resonant tunneling, alternate metal-dielectric strata become transparent. Furthermore, negative permittivity of metals demonstrates negative refraction for p-polarized waves [2].

Coupling of adjacent nanomembranes gives rise to novel nonlocal effects. Recently it has been demonstrated that a single traveling beam in a homogeneous dielectric medium that impinges on a metallodielectric lattice is able to excite a couple of wave fields with opposite refraction [3]. This can be understood by considering independent dispersion curves for each beam diffracted in the metamaterial. In terms of the effective medium theory we would find an elliptic curve and also a hyperbolic curve. However Rytov approximation [4], later followed by Yeh [5], is not consistent with both curves simultaneously.

In this contribution we follow an approach leading to a single elliptic curve that allows a complete description of both refractive behaviors concurrently. Importantly, only two parameters of the closed curve (the semi-axes of the resultant ellipse) together with the lattice period fulfill a complete description of indefinite birefringence. For that purpose, wideness of the ellipse shall exceed that of Brillouin zone. Unfortunately, this leads to an erroneous conduct in the vicinity of the band edges where Bragg reflections govern dispersion. Finally our semi-analytical approach is extended to more general situations straightforwardly, including when a single plasmonic band appears and when more-than-two bands come into play.

[1] P. Chaturvedi et al. "A smooth optical superlens," Appl. Phys. Lett. 96 (2010) 043102.

[2] M. Scalora et al., "Negative refraction and sub-wavelength focusing in the visible range using transparent metallodielectric stacks," Opt. Express 15 (2007) 508

[3] A.A. Orlov et al., "Engineered optical nonlocality in nanostructured metamaterials," Phys. Rev. B 84 (2011) 045424.

[4] S.M. Rytov, "Electromagnetic properties of layered media," Sov. Phys. JETP 2 (1955) 466.

[5] A. Yariv and P. Yeh, "Electromagnetic propagation in periodic stratified media. II. Birefringence, phase matching, and x-ray lasers," J. Opt. Soc. Am. 67 (1977) 438.

8423-66, Poster Session

Non-volatile bi-directional all-optical switching in chalcogenide glass metamaterials

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For the first time, we demonstrate a non-volatile bi-directional all-optical switching in a phase-change metamaterial. By engaging together the phase-change functionality of a chalcogenide glass and the resonant plasmonic properties of a nanostructured metamaterial we have achieved high-contrast optical modulation of transmission and reflection. Light-induced structural phase transitions in the glass component of hybrid structures provides for reversible switching of optical properties across large-scale metamaterial arrays.

Phase transitions are initiated uniformly across large (~2000 µm^2) areas of the chalcogenide film by single-pulse laser excitation on the nanosecond timescale. Reversible switching in the 1-2 µm spectral range with a reflection contrast ratio exceeding 4:1 has been achieved at optical excitation levels of ~0.25 mW/µm^2 in a gold metamaterial hybridized with germanium-antimony-telluride glass - a device structure only ~1/8 of a wavelength thick. Such metamaterials may be structurally engineered to provide switching functionality throughout the chalcogenide's visible to mid-infrared transparency range.

8423-67, Poster Session

Optimization of field propagation in optical coaxial nano-waveguides of complicated form

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The artificial optical systems consist of subwavelength elements in the cross-section play now key role in the way of miniaturization of optical components. The goal is to create optical nano-size waveguides to support the propagation of light to a needed distance with small losses. As known, photonic crystal fibers with subwavelength channels characterized by electromagnetic fields delocalization in the cross-section. The other way is to use surface plasmon-polaritons propagating in noble metals. However, light propagation length is very short in plasmonic waveguides as compared with optical fibers. Thus, a very important task is to reduce absorption losses in waveguides keeping their nanoscale sizes. As was found, coaxial waveguides made of noble metals support propagation of the azimuthally-symmetric TEM-like plasmonic mode in the optical range with smaller attenuation and without cutoff. Earlier we proposed the coaxial waveguides made of glasses and noble metals with nano-size cross-section in which the bulk inner metal rod is replaced by one or several thin metal tubes filled by dielectric inside. The strong subwavelength field localization in dielectric area inside inner tube, low losses and appropriated propagation length have been achieved. The development of this task by FEM method founded on a direct numerical solution of Maxwell equations with proper boundary conditions is present here.

The set of advanced structures are studied: a conventional coaxial; a coaxial waveguide with periodically arrange metal tubes for reducing the metal part in the structure; the coaxial waveguides with elliptic-type central rod and two cross ellipses. A combination of noble metal with active glasses has been estimated towards minimization of losses. The power flow distribution for different types of modes is investigated. The best characteristics can be achieved for the dipole-like modes which can be excited by an external dipole. The simulation of the field excitation on the end of indicated above waveguides is implementing. The affects of the asymmetry of the central part those structures has been estimated. This is very important problem due to manufacturing complexity. We have concluded that drift from axis of symmetry or variation of symmetry of the central part of structure considerably affected on characteristics of the field propagation. The permissible variations are defined. The comparison of the results of this investigation by wavelength deviation has been performed. The requirements specifications for manufacturing of the optimum kind waveguide with appropriate parameters are formulated.

Considered waveguide structures can be fabricated using the state-of-the-art techniques for producing photonic crystal glass. Complicated micro- and nanostructures manufacturing is possible via multiple redrawing and sintering of glass stacks. Such nano-sized waveguides can be used as optical near-field probes and for transfer of images with subwavelength resolution.

8423-68, Poster Session

Metamaterial engineering of plasmonic metal luminescence

M. Ren, ORC Univ. of Southampton (United Kingdom) and Nankai Univ. (China); G. Adamo, E. Plum, J. So, K. F. MacDonald, ORC Univ. of Southampton (United Kingdom); J. Xu, Nankai Univ. (China); N. I. Zheludev, ORC Univ. of Southampton (United Kingdom)

While metamaterials research has been focused on engineering the electric, magnetic and nonlinear responses of periodic sub-wavelength metallic structures, we show for the first time that metamaterial structuring can also be used to engineer the luminescent properties of this metal framework.

We demonstrate this experimentally by creating new luminescent bands in metallic gold. While the natural luminescence spectrum of bulk gold is dominated by a peak at about 516 nm resulting from the Fermi level to d-band transition, nanostructuring can create new, intense luminescent lines at frequencies anywhere below the natural band.

The wavelength of the new artificial emission line is linked to the plasmonic mode of metamaterial and its wavelength scales with the metamaterial's unit cell size. Using optical excitation at 400 nm we observed resonant emission in the range from 640 to 710 nm, controlled by scaling the nanostructure. Similar luminescent bands were observed in cathodoluminescence experiments.

8423-69, Poster Session

From nonlinear optics to nonlinear plasmonics: giant nonlinear optical activity in a metamaterial

M. Ren, ORC Univ. of Southampton (United Kingdom) and Nankai Univ. (China); E. Plum, ORC Univ. of Southampton (United Kingdom); J. Xu, Nankai Univ. (China); N. I. Zheludev, ORC Univ. of Southampton (United Kingdom)

In 1951, Sergey Vavilov predicted that birefringence, dichroism and polarization rotatory power should be dependent on light intensity. It required the invention of the laser to observe the barely detectable effect of light intensity on the polarization rotary power of the optically active lithium iodate crystal, the phenomenon now known as the Nonlinear Optical Activity, a high-intensity counterpart of the fundamental optical effect of polarization rotation in chiral media. Here we report that a plasmonic metamaterial exhibits Nonlinear Optical Activity 40 million times stronger than lithium iodate crystals thus transforming this fundamental phenomenon of polarization nonlinear optics from an esoteric phenomenon into a major effect of nonlinear plasmonics with potential for practical applications.

Observation of this giant polarization effect provides a powerful illustration that nanoscale nonlinear plasmonics of metamaterials offers extremely strong effects unfolding in nanoscale volumes of nonlinear medium that could lead to applications in modulation of light intensity and polarization in nanophotonic devices.

8423-70, Poster Session

Coherent emission from plasmonic metamaterials

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We report on a fundamentally new radiation phenomenon in nanostructures: emission of spatially coherent and spectrally narrow-band light driven by localized injection of free electrons into a planar plasmonic metamaterial. In 'coherent' metamaterials, where interactions among the meta-molecules are strong, an electron beam can generate a synchronized, in-phase response across a large number of meta-molecules leading to threshold-free emission of spatially coherent light propagating perpendicular to the metamaterial.

In a laser, coherence is derived from the bosonic statistics of photons, the resonant properties of the laser cavity and the collective nature of stimulated emission in the gain medium, and a threshold level of input energy is required to maintain the gain and overcome losses. Here we show experimentally that a scalable low-divergence, threshold-free optical source can be constructed on the basis of a collectively oscillating optical nano-antenna array formed by the metamaterial wherein coherence is provided not by the feed (as in conventional microwave antenna arrays) but via the strong mutual interactions among the nano-antennas.

8423-71, Poster Session

Optical gecko toe: near-field force sticks a metamaterial to any surface

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We have identified a new type of optically-driven force, the near-field force of attraction between an illuminated planar plasmonic metamaterial and a dielectric or metallic surface. This force provides an optically controlled adhesion mechanism mimicking the gecko toe van der Waals attraction. It can be orders of magnitude stronger than conventional radiation pressure, can exceed the Casimir forces in the system and at illumination intensities of just a few tens of nW/μm^2 it can overcome the Earth's gravitational pull on a metamaterial located within a few tens of nanometres of a surface.

This newly identified near-field force has a resonant nature linked to the confinement of energy in the metamaterial's plasmonic mode and acts to close the gap between the metamaterial film and the surface. It has been evaluated for different types of metamaterial using both the Maxwell stress tensor formulism and the energy gradient approach, which coincide in predicting the magnitude and the resonant frequency dependence of the force on the wavelength of external excitation.

The near-field force holds considerable advantages for nanoscale manipulation in that it depends on both light intensity and wavelength - offering dynamic controllability and spectral selectivity. It may serve applications in optical trapping/tweezing and in the control of light with light via optically reconfigurable metamaterials.

8423-72, Poster Session

Nano-electro-mechanical switchable (NEMS) photonic metamaterial

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Lack of tunability is a key challenge for metamaterials, whose unique properties are usually fixed and limited to a single resonant wavelength. Here we introduce nano-electro-mechanical switchable (NEMS) photonic metamaterials as a flexible platform for large-range tuning, switching and modulation of metamaterial properties in the optical part of the spectrum.

We tune, switch and modulate the optical properties of metamaterials by controlling the spacing and thus coupling between nanoscale metamaterial resonators. The meta-molecules are placed on electrically conductive, flexible support structures, the spacing of which depends on electrostatic forces resulting from an applied voltage. For small applied voltages the electrostatic force is balanced by the elastic restoring force of the support structures, giving rise to continuously tunable optical properties, which can be modulated at rates in excess of 100 kHz. However, when the applied voltage is increased beyond 5.7 V the electrostatic force overcomes the restoring force, resulting in high-contrast, step-like switching of the metamaterial's optical properties including a 15% red-shift of its resonance and a 72% reflectivity change in the telecommunications band around 1500 nm.

Apart from fast modulation, tuning and high-contrast switching of their optical properties, voltage-controlled NEMS photonic metamaterials easily integrate with electronics, making them a flexible and practical solution for tunable metamaterial devices.

8423-73, Poster Session

Ultrafast nonlinearity of graphene metamaterial

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We demonstrate for the first time that the nonlinear optical response of a monoatomic graphene layer can be drastically enhanced by hybrization with a plasmonic metamaterial.

The nonlinear optical properties of graphene are non-resonant in a broad spectral range from the visible to the near-IR establishing graphene a very attractive candidate for laser mode-locking applications. However, the nonlinearity of graphene is small and close-to-breakdown levels of excitation are required to engage it. Here, we show that nonlinear changes of transmission of a hybrid graphene-metamaterial structure can be resonantly increased by at least a factor of 20 while retaining an ultrafast (~100 fs) response time. This is achieved by engaging the enhanced local fields associated with the metamaterial resonances. Our approach allows to engineer and enhance graphene's nonlinearity within a broad wavelength range.

8423-74, Poster Session

Light absorption by interference of radiation in a metamaterial: an anti-LASER

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We demonstrate for the first time that a planar photonic metamaterial (a single layer of nanostructured metal less than one tenth of a wavelength thick) can, via a coherent interaction, resonantly absorb all of the light incident on it.

The coherent absorption phenomenon described here is a metamaterial analogue of the recently reported optical cavity 'coherent perfect absorption' phenomenon - the time-reversed counterpart of conventional lasing. It is a narrowband phenomenon arising from the tailored interplay of interference and absorption between counter-propagating beams in a dissipative medium and was recently demonstrated experimentally in a bulk optical resonator [Wan, et al., Science 331, 889 (2011)].

Here we show that a similar effect may be observed in a single sub-wavelength metallic metamaterial film exploiting plasmonic resonant absorption. We experimentally demonstrate coherent perfect absorption in a 50 nm thick gold metamaterial at a wavelength of 633 nm and show that the level of absorption can be coherently controlled by adjusting the mutual phase of the interfering beams.

The metamaterial coherent perfect absorber is the time-reversed counterpart of the 'lasing spaser' (a coherent source of optical radiation fuelled by plasmonic oscillations) and may serve applications in optical modulators, transducers, switches or sensors.

8423-75, Poster Session

Electro-optical modulation of sub-terahertz radiation in a superconducting metamaterial

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We report the first demonstration of electro-optical modulation of millimetre-wave radiation using a superconductor metamaterial. High-contrast intensity and phase modulation is achieved via the distruction of the superconducting state by current running through the metal network of niobium metamaterial. The asymmetrically split-ring niobium metamaterial at temperatures below Tc supports a Fano-type mode of excitation associated with high-quality resonances (Q~130) in its transmission and absorption spectra. Current up to 700mA running through the niobium network of metamolecules is sufficient to induce a phase transition in the superconductor which is accompanied by an increase of the Joule losses and a degradation of the Fano resonance. A nearly 100% modulation of the metamaterial's transmission and reflection at the resonance frequency of about ~100GHz has been demonstrated. We also demonstrated a 500kHz amplitude modulation of the sub-terahertz carrier signal and believe that the modulation rate can be improved further.

8423-76, Poster Session

Light localization, linear, and nonlinear properties of disordered plasmonic metamaterials

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Here, we report for the first time an experimental study of the effects of deliberate disorder on the far-field, near-field and nonlinear properties of coherently illuminated plasmonic metamaterials that support strong cooperative behaviour. Multiple scattering phenomena in disordered electromagnetic media are becoming increasingly important anddisorder is no longer considered an unwanted disturbance on perfect periodicity, but can be used to tailor the performance and enable new functionnalities. Here, we report on the effects of disorder on metamaterials that support strong cooperative behaviour and observe a rapid decay of resonance features accompanied by a change in the statistics of the scattered fields. In particular, we study for the first time the near-field intensity fluctuations of the waves scattered by planar metamaterials. We show that introducing disorder leads to increasing inhomogeneity in the near-field speckle patterns and discuss the relation of the latter to the metamaterial resonant behaviour. We put forward disorder-induced collective phenomena as means to tailor the near- and far-field linear, as well as non-linear properties of planar metamaterials and investigate two-photon absorption enhancement in such materials.

8423-77, Poster Session

Toroidal plasmonic metamaterial

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We report on the development of toroidal metamaterials operating in the near-to-far IR spectral range. The toroidal metamaterials is a recently demonstrated novel class of artificial media with the resonant macroscopic response determined by a peculiar and previously disputed fundamental type of microscopic dipolar excitations, the toroidal dipole. Taking into account limitations of the most suited fabrication techniques (namely Sandia's projection lithography SAMPL and NTU's e-beam lithography with precise alignment technique) and using realistic data for the optical properties of the constituent dielectrics and metals, we have come up with a substantially optimised design of such metamaterials capable of producing dominant toroidal response at IR frequencies. We have also investigated the possibility of enhancing toroidal response by incorporating gain into the metamaterials' structure.

8423-78, Poster Session

Flux exclusion quantum superconducting metamaterial

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We propose a new principle of quantum electromagnetic metamaterias based on the magnetic flux quantization in closed superconductor loops that offers a quantum level nonlinearity. Unlike recently introduced metamaterial based on SQUID arrays (Superconductor QUantum Interference Device), our new metamaterial requires no Josephson Junctions, making the manufacturing process significantly simpler. We implemented our design for mm-wave range out of Niobium and YBCO superconductor films and performed a full electromagnetic characterization in the mm-wave range across a transition to the superconducting state.

8423-79, Poster Session

Femtosecond polarization conversion with plasmonic crystals

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Polarization properties of the surface plasmon-polaritons (SPP) allow one to use plasmonic nanostructures as polarizers and waveplates of submicron thickness. On the other hand such plasmonic structures strongly affect the shape of femtosecond laser pulses transmitted or reflected from the sample. Symmetry considerations lead p- and s- state of polarization (SoP) to be the eigenstates of such 1D metallic nanostructures. However, if one sends a linear combination of these states onto a plasmonic metallic nanograting the evolution of the SoP inside a single pulse becomes complicated. In this paper we use surface plasmons to induce a remarkable state of polarization (SoP) alteration inside a single sub-picosecond laser pulse reflected from a plasmonic crystal.

The samples of plasmonic crystals were fabricated by thermal sputtering of 50-nm gold layer onto a polymer diffraction grating with the period compatible with the wavelength of used femtosecond laser. The reflection spectra of the sample under different angles of incidence reveal the minima associated with the band structure of SPP as well as a SPP band gap. The results of the measurements for p- and s-polarized incident SoP demonstrate a considerable alteration of the femtosecond pulse shape by the SPPs. A delay of about 150 fs is seen between the measured pulses for orthogonal input SoPs. Time-resolved femtosecond-resolution measurements of sub-picosecond polarization conversion demonstrate the variation of the SoP from the horizontal one to the vertical one along with the non-coherent mixing of horizontally and vertically polarizations in between.

It reveals the complicated behavior of the polarization inside a single laser pulse including switching from the vertically polarized state to the horizontally polarized state as well as time-dependent depolarization.

8423-80, Poster Session

Engineering interface singularities with metamaterials: planar optical prism and diffraction grating

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We report the first experimental realization of planar optical dispersion elements mimicking the functionalities of a free-space prism and a diffraction grating.

The electromagnetic response of thin layer of metamaterial film depends on the dimensions and geometrical shape of the metamolecules and the spacing between them. By varying these parameters, any arbitrary amplitude and phase response can be designed, giving an incredibly flexible platform for engineering devices of sub-wavelength thickness.

Here we demonstrate metamaterial equivalent of two examples of refractive optics; the diffraction grating and the prism.

A planar metamaterial pattern consisting of repeated narrow strips of rings has been demonstrated that mimics the response of a blazed diffraction grating for optical to near-infrared wavelengths.

In a different design, a rectangular array of ring metamolecules with gradient variation of parameters along one direction is shown to exhibit the dispersion characteristics of a three-dimensional glass prism.

8423-81, Poster Session

Cooperative asymmetry-induced transparency in ensembles of interacting plasmonic resonators

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We develop a theory of Cooperative Asymmetry Induced Transparency (CAIT) in a finite array of interacting meta-molecules. In contrast with similar EIT like phenomena in metamaterials that can be described by meta-molecules acting independently, CAIT relies on cooperative interactions to form the high quality modes on which the transparency depends.

Generally, an otherwise opaque or reflective material can be made transparent by coupling two material states. A probe field excites a state that scatters the light in the absence of coupling; while the other is stable and cannot be directly addressed by the probe. In a transparency window, the coupling induces excitation of the stable state at the expense of the optically active excitation, suppressing scattering of the probe. The most well known example of this phenomenon is electromagnetically induced transparency (EIT) in atoms. Coupling induced transparency has also been observed in metamaterials, where sub-wavelength arrangements of circuit elements, or meta-molecules, rather than atoms, serve as the constituent EM emitters. Each meta-molecule, consisting of two meta-atoms, supports two modes of current oscillation: one driven by the probe, and the other blind to the probe. An effective coupling between these two modes can be achieved by engineering the meta-molecules' geometry, and in particular can be induced by breaking of the meta-molecules' symmetry. The models however assume the blind mode of a single meta-molecule is itself radiatively stable. For many meta-molecules, however, this assumption does not hold.

Here, we develop a model for an array of meta-molecules where the stable excitation responsible for coupling induced transparency emerges from a collective mode distributed over the entire metamaterial. We arrive at this model from a framework that describes meta-atoms as of discrete oscillators whose interactions are mediated by the scattered electromagnetic fields. Whereas both modes of a single meta-molecule radiate, the interactions between them form a stable collective mode blind to the incident field which facilitate CAIT.

8423-82, Poster Session

Light transmission spectra in a symmetrical fibonacci metamaterial structure

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In this work we investigate the transmission spectra of a light beam normally incident from a transparent medium into a binary one-

dimensional quasiperiodic multilayer photonic structure made up of both positive (SiO2) and negative (metamaterial) refractive index materials with a mirror symmetry. The quasiperiodical structure follows a symmetrical Fibonacci (FB) substitutional sequences, which can be viewed as a superposition of two Fibonacci structures with mirror reflection at the center. The advantage of a symmetrical Fibonacci superlattice is its ability to offer perfect transmission peaks due to its internal coupling between localized and propagation modes: thus it can be used as ideal optical filters.

Although several theoretical techniques have been used to study the transmission spectra in these structures, in the present work we make use of the transfer matrix approach to analyze them, simplifying the algebra which would otherwise be quite involved.

The optical transmission spectra presents many perfect transmission peaks (the transmission coefficients are equal to the unity), as well as a unique mirror symmetrical profile around the midgap frequency Ω (which is the midgap frequency of a periodic quarter-wavelength multilayer). Besides, the structure is transparent at some reduced frequencies forming two broad peaks, distributed symmetrically around Ω. Furthermore, the transmission spectrum has a six-cycle self-similar behavior with respect to the generation number of the symmetrical FB sequence, within a symmetrical interval around Ω, for the range of frequency reduced by a scale factor approximately equal to 25.

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8423-83, Poster Session

Phonon polaritons in metamaterial photonic crystals at terahertz frequency range

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In this work we investigate the phonon-polariton band gaps in periodic and quasi-periodic (Fibonacci-type) multilayers made up of both positive (SiO2) and negative refractive index materials (metamaterials) following the Fibonacci sequence in the terahertz region. The behavior of the polaritonic band gaps as a function of the multilayer period is investigated systematically. Our theoretical model makes use of a transfer matrix approach to simplify the algebra involved and to set up analytical phonon-polariton dispersion relations (bulk and surface modes). We also present a quantitative analysis of the results, pointing out the distribution of the allowed polaritonic bandwidths for high Fibonacci generations, where we proceed with an analysis of the confinement effects arising from the competition between the long-range aperiodic order, which is induced by the quasi-periodic structure, and the short-range disorder, which gives good insight about their localization and power law.

The quasi-periodic structure follows the Fibonacci substitutional sequence and can be generated by the following inflation rule: A→AB and B→A, where A (metamaterial) and B (SiO2) are the building blocks modeling it. Neglecting any damping term (when losses of the metamaterial are considered, the damping factor can be defined as a fraction of the phonon frequency), the metamaterial possesses the negative refractive index in the THz region, whose corresponding dielectric permittivity [1] and magnetic permeability [2] exhibit a negative refraction index at THz range .

We have observed that the effects of the introduction of the negative refractive index material in the polariton spectra are more accentuated in the intermediate region of the dispersion relation, where bulk exists and surface modes are with backward behavior, which is a typical property of metamaterials. Furthermore, the polariton spectra also show two modes, in upper and lower frequency intervals, where we have only forward modes, which are typical of positive refractive index material. We also have focused our interest to the case where the average index of refraction of the photonic crystal vanishes, the so-called-zero-band gap region, where the band gaps are different of the usual Bloch band gaps.

[1] H. J. Falge and A. Otto,Phys. Status Solidi B 56, 523-534 (1973).

[2] T. J. Yen, W. J. Padilla, N. Fang, D. C. Vier, D. R. Smith, J. B. Pendry, D. N. Basov, and X. Zhang, Science 303, 1494-1496 (2004).

8423-84, Poster Session

Experimental demonstration of dispersion engineering through mode interactions in plasmonic microcavities

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Flat dispersion in plasmonic structures is critical for realizing subwavelength imaging, since evanescent waves in a large spatial frequency range can be coupled and enhanced. As we have demonstrated in previous studies, a plasmonic microcavity with two periodically corrugated metallic mirrors is a flexible system to engineer the dispersion of plasmons and Fabry-Perot (FP) cavity modes [1], which enables a far-field subwavelength imaging [2].

In this contribution we demonstrate experimentally how the dispersion of the positively dispersive FP mode is modified due to the strong interaction with the negatively dispersive plasmons [1]. The cavities, consisting of two 2D corrugated Ag-films, were fabricated on a self-assembled multi-domain monolayer polystyrene crystal. The dispersions in transmission were measured at incident angles from 0° to 80°. We observe, for instance, that in the cavity with a cavity length of 250 nm, the first FP mode at p-polarization is fixed within an angle of ±20° around 890 nm, while at s-polarization it remains fixed at least within ±10°. With a reduced cavity length, the dispersion of the FP mode becomes even negative. We will show that these results are of great importance for scanless far-field subwavelength imaging and other applications such as slow light waveguides in photonic integrated circuits and 2D omnidirectional polarization independent filters.

[1] L. Fu, P. Schau, K. Frenner, W. Osten, T. Weiss, H. Schweizer, and H. Giessen, Phys. Rev. B, in press, (2011).

[2] P. Schau, K. Frenner, L. Fu, H. Schweizer, H. Giessen, W. Osten, Optics Express 19, 3627 (2011).

8423-93, Poster Session

Tunable metamaterials: a comparative study of different geometries and modulation mechanisms

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During the last two decades, substantial progress has been achieved in the development of terahertz (THz) science and technology. However, there are several restrictions which limit the development of fruitful applications within the full THz frequency region. One of the main constraints is the so called "THz gap," which is basically due to the lack of appropriate responses, at those frequencies, from many naturally existing materials. The use of metamaterials can be the right solution.

Since the first extensive studies on metamaterials, most of the attention has been focused on the passive control and linear properties of these composite structures. However, their full exploitation requires the ability to dynamically control their properties in real time, through either direct external tuning or nonlinear responses. Different strategies have been explored in order to achieve tunability in the resonating inclusions within various ranges of frequencies, from microwaves to the THz region, including the use of different kinds of capacitors, microelectromechanical systems (MEMS), photodoping, or liquid crystals (LC). We designed metamaterial-based devices which can be frequency-tuned by using different modulation mechanisms. We modelled periodic structures consisting of different "unit cells" based on the concept of split ring resonator. In order to study the device responses in the frequency region of interest, we carried out several numerical simulations via commercial electromagnetic software. Moreover, we explored several tunability mechanisms for such resonators within various ranges of frequencies, from microwaves to the THz region, including the use of different kinds of capacitors, microelectromechanical systems, or liquid crystals. Experimental measurements are currently under way.

8423-43, Session 10

Metamaterials for active photonics and energy conversion

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Metamaterials have compelling potential applications in active photonics and solar energy conversion. Highly compliant substrates allow generation of actively tunable metamaterials based on split ring resonators with frequency tunability over several resonant linewidths, and applications in sensing and spectroscopy. We discuss frequency tunable metamaterials with greater-than-line-width tunability (~400 nm) in the 2 - 5 micron range, using the mechanical deformation of an elastomeric substrate to modify the distance between resonant elements thus changing the coupling strength. Compliant optical metamaterials can be used to perform tunable surface-enhanced infrared absorption by tuning the metamaterial resonant frequency through a molecular vibrational mode at infrared wavelengths, enhancing the infrared reflection signal from the vibrational mode by a factor of almost 200. Metamaterials can also enable control of light-matter interactions in solar energy conversion, leading to enhanced light-trapping and absorption, as well as increased open circuit voltage and enhanced quantum efficiency in solar photovoltaic structures. We have demonstrated an ultrathin (260 nm) metamaterial super absorber consisting of a metal-insulator-metal stack with a nanostructured top silver film composed of crossed trapezoidal arrays. The super absorber yields broadband and polarization-independent resonant light absorption over the entire visible spectrum (400-700 nm) with an average measured broadband absorption of 0.71 and simulated absorption of 0.85. The trapezoidal shaped subwavelength elements support multiple transverse and longitudinal modes, unlike gratings and other nonergodic, high-symmetry shaped, and as a result exhibit much broader absorption. It was also found that the absorbance was quite insensitive to light incident angle. These new nanostructured absorbers open a path to realize ultrathin black metamaterials based on broadband resonant absorption.

8423-44, Session 10

Nonlinear responses in optical metamaterials: theory and experiment

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Metamaterials have recently attracted widespread interest due to their intriguing properties not found in ordinary materials. They are artificial electromagnetic (EM) materials composed of subwavelength local resonant structures of electric and/or magnetic type, and can possess arbitrary values of effective permittivity and permeability dictated by resonant structures. The linear wave properties of metamaterials have been extensively studied in the past several years, with many exciting new phenomena predicted or demonstrated.

In recent years, there have been a number of reports on studies of nonlinear optical properties of metamaterials. The first attempts were mainly theoretical; experimental works appeared only recently. It was originally suggested by Pendry et al. that enhanced nonlinear optical responses could be observed in metamaterials composed of split ring resonators (SRR) at the magnetic resonances [1]. In a series of recent experiments [2-3], significantly enhanced second-harmonic generation (SHG) signals were indeed observed in planar arrays of gold SRRs at their magnetic resonance frequencies, but the SHG signals were obtained at a single frequency. Later, the spectra of SHG around the magnetic resonance for a fishnet metamaterial structure were measured, exhibiting strong enhancement at the resonance [4]. Unlike in a molecular system, the resonant enhancement came from local-field enhancement due to magnetic resonance at the input frequency. However, detailed theoretical calculation in comparison with experiment has not yet been attempted, and quantitative understanding of the observations is still lacking.

Here, we report combined theoretical and experimental efforts to study SHG from a fishnet structure [5]. It consists of a sandwiched structure of Ag/SiO2/Ag layers with an array of periodic square holes. The structure was deposited on a silicon substrate. It was designed to have a magnetic resonance around when a normally incident beam was linearly polarized along the thin stripes.

We used a theoretical approach that combined finite-difference-time-domain (FDTD) simulation with a field integration technique to calculate the second harmonic (SH) response from the metamaterial. The calculated and experimentally measured SHG spectra of different polarization combinations, normalized against the SH signal of P-in/P-out polarization combination from a flat Ag film. The calculated SHG spectra show quantitative agreement with the experimentally measured spectra of P and S polarization combinations. The maximum resonance enhancement of SHG reaches ~80 times of that from a flat Ag surface for the P-in/P-out polarization combination, suggesting that metamaterials could be potentially useful as nonlinear optical materials in some applications. The resonant enhancement of SHG from a metamaterial is through the resonant enhancement of local field, and is dominated by some “hot spots” in the structure. The P-polarized SH output is much stronger than the S-polarized one, irrespective of the input polarization, which can be explained by the symmetry argument.Furthermore, our theoretical calculations also help us understand the details of many interesting phenomena observed experimentally, and allow us to design optimal structures that would yield the highest harmonic or other wave mixing outputs.

REFERENCES

1.J. B. Pendry, A. J. Holden, D. J. Robbins, W. J. Stewart, IEEE Trans. Microw. Theory Tech. 47, 2075 (1999)

2.M. W. Klein, C. Enkrich, M. Wegener, and S. Linden, Science 313, 502 (2006)

3.M. W. Klein, M. Wegener, N. Feth, and S. Linden, Opt. Express 15, 5238 (2007)

4.E. Kim, F. Wang, W. Wu, Z. Yu, and Y. Ron Shen, Phys. Rev. B 78, 113102 (2008)

5.S. W. Tang, D. J. Cho, H. Xu, W. Wu, Y. R. Shen, and L. Zhou, Opt. Express 19,18283 (2011)

8423-45, Session 10

Second harmonic generation in plasmonic nanoresonators

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The second order nonlinear response from flat metal screens has been widely investigated, both theoretically and experimentally, from the late 1960s-1980s. The last few years witnessed renewed interest in the study of nonlinear second order properties of metal/dielectric composites thanks to the development of nanotechnologies and nanoscience. We study second harmonic generation from dipole gold nanoantennas by analyzing the different contributions of bulk and surface nonlinear terms. Numerical calculations have been performed applying a Green’s tensor method. The SHG as a function of the wires cross section size is investigated in both the near and far field regimes. We show that the excitation of localized surface plasmon polaritons in these structures can remarkably modify the nonlinear response of the system by enhancing surface and/or bulk contributions, creating regimes where bulk nonlinear terms dominate over surface linear terms and vice versa. We also report results of calculations performed on Silver coupled 2D-nanoresonators. Coupling is responsible for the formation of resonant modes that can be localized on small portions of the structure or distributed over the

whole structure. Different field profiles can be obtained by varying the parameters of the input field (i.e. the wavelength). The radiation pattern of the generated SH field is obtained by considering linear scattering and the structure behaves as an antenna for the SH field. We note that different configurations of the pump field lead to different SH far-field emission patterns. The effect of complex structures is considered and discussed putting into evidence that angular emission profile of the SH field contains information about the spatial location of the pump field hot spots at different frequencies. Finally, applications to a new class of sensors and nonlinear nano sources are discussed.

8423-46, Session 10

Nonlinear magnetooptic light control of metamaterial waveguides

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The control of light propagating in complex waveguides is an important global topic and nonlinearity is a critically important property. In this context the use of metamaterials is seminal to the development of new devices. Changes to the boundary conditions show that even modest amounts of power introduces elegant control of the effective group velocity and if this is coupled with the very broad permittivity and permeability variations that modern metamaterials are expected to exhibit a new domain of integrated circuits begins to emerge. Magnetooptics is a discipline that is known globally to be a powerful mechanism for control as well and it is important to add their its influence to metamaterial complex systems. Through magnetooptics many novel applications emerge but when combined with for example permittivity near to zero metamaterials the future for nonlinear integrated systems looks very exciting. In the early part of the presentation significant waveguide complexity will be introduced and will be analysed with a novel nonlinear transformation approach that identifies a form dramatic self-focussing that will be discussed later on. The role of magnetooptics will be assessed though the classic Cotton-Mouton/ Kerr effects, Faraday orientation with coupled polarisations and Polar [magnetic field perpendicular to the interface] orientations. It will be shown that light stopping and the manipulation of certain types of planar waveguide interfaces leads to dramatic coupler behaviour both in the transverse magnetic field cases and the TM-TE coupled-mode Faraday configuration. Ridge waveguides will be shown to have very strong practical implications for light gathering formats. This will be illustrated by a nonlinear electromagnetic field (energy) concentrator based upon a new method of investigating this type of phenomenon and it will be demonstrated that superfocusing, which includes consequent linear and nonlinear focusing, is highly developed. The new approach reported here includes two connected techniques: complex geometrical optics and a full-wave nonlinear set of solutions. The possibility of nonlinear superfocusing of energy the formation of “hot spot(s)” is predicted and, furthermore, this nonlinear focusing and switching occurs precisely whenever the input field intensity exceeds some “threshold” value. All of these effects will to be very sensitive to magnetooptic control.

8423-47, Session 10

Intrinsic localization in nonlinear and superconducting metamaterials

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“Metamaterials” are usually meant to be periodic arrangements of artificially structures elements designed to achieve advantageous and/ or unusual electromagnetic properties. The last decade they attracted a lot of interest that originates from their great potential for novel applications. There have been many efforts to increase their performance and bring their oparation frequency to the optical. At the same time, the construction of nonlinear metamaterials offers real-time tunability of their macroscopic parameters via an external field. However, significant losses place a strict limit on the performance of conventional metamaterials, hampering thus any progress toward their practical use. Superconducting metamaterials provide a dramatic reduction of losses accompanied by inherent nonlinearities an extreme sensitivity to external fields.

We investigate intrinsic localization both in conventional and superconducting discrete metamaterial models. While the former become nonlinear by the inclusion of nonlinear electronic components in each of their elements, the latter may be intrinsically nonlinear due to the Josephson effect. The combined effects of nonlinearity and discreteness may lead to the generation of nonlinear excitations in the form of dissipative discrete breathers, dynamically self-localized modes that may result from a balance of the incident power due to an applied field and the intrinsic losses. The existence and stability of several types of discrete breathers, some of which may co-exist, has been demonstrated both in conventional, split-ring resonator - based and SQUID-based metamaterial models. Discrete breathers break homogeneity of the system’s response by changing locally the magnetic response of the arrays from diamagnetic to paramagnetic (or vice versa). Moreover, power in nonlinear magnetoinductive transmission lines can be transmitted effectivelly through nonlinear channels, that makes possible to fabricate contact-free data and power transfer devices.

8423-48, Session 11

Nonlinear and reconfigurable metamaterial components

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By leveraging the capabilities of photonics (speed) and of electronics (compactness), it should be possible to realize high performance integrated opto-plasmonic systems with applications from high bandwidth communications to sensing, and beyond. Such integration requires the availability of ultra-compact, ultra-fast, reconfigurable and tunable photonic components.

In this work, we propose and design such reconfigurable electromagnetic (EM) components. As an example we discuss in detail a lens that has a variable focus such that its output field profile can be tuned from an unfocused beam to a highly localized beam. Such lens features an extended focal region that can be moved from infinity towards the lens surface by changing the intensity of the incident beam. Two configurations of the device will be discussed: i) self-focusing beam and ii) all-optically externally controlled focusing. We discuss our initial steps toward experimental realization of the proposed structures.

8423-49, Session 11

Nonlinear lasing-dynamics of gain-enhanced nanoplasmonic metamaterials

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We study the nonlinear lasing-dynamics of nanoplasmonic metamaterials. Developing a new microscopic ab initio Maxwell-Bloch Langevin approach [1,2] that incorporates quantum noise into the Maxwell-Bloch theory for active nanoplasmonic metamaterials [3,4] allows us to integrate the two prevalent forms of light and plasmon emission, amplified spontaneous emission (ASE) and coherent stimulated emission, into a self-consistent theoretical framework. For the example of a gain-enhanced double-fishnet structure (Figure 1) we report that lasing of the bright negative-index mode is possible if the higher-Q dark mode is discriminated by gain, spatially or spectrally.

A dynamic nonlinear competition of lasing states during the transient phase is followed by steadystate emission where bright and dark modes can coexist. We analyze the influence of pump intensity and polarization and explore methods for mode control. In particular, as the competition between bright and dark modes as well as schemes for mode control depend on the geometry a structural variation allows to completely

suppress excitation of the dark mode and nonlinear dynamic competition between the two bright modes of orthogonal polarization can be observed.

References

[1] A. Pusch, S. Wuestner, J. M. Hamm, K. L. Tsakmakidis, and O.~Hess, "Coherent Amplification and Noise in Gain-Enhanced Nanoplasmonic Metamaterials: A Maxwell-Bloch Langevin

Approach", submitted, (2011).

[2] S. Wuestner, J. M. Hamm, A. Pusch, F. Renn, K. L. Tsakmakidis, and O. Hess, "Control and dynamic competition of bright and dark lasing states in active nanoplasmonic metamaterials", submitted (2011).

[3] S. Wuestner, A. Pusch, K. L. Tsakmakidis, J. M. Hamm, and O.~Hess, "Overcoming Losses with Gain in a Negative Refractive Index Metamaterial", Phys Rev Lett 105, 127401 (2010).

[4] J. M. Hamm, S. Wuestner, K. L. Tsakmakidis, and O.~Hess, "Theory of Light Amplification in Active Fishnet Metamaterials", Phys Rev Lett 107, 127401 (2011).

8423-50, Session 11

Compensation of plasmonic losses in metamaterial using nonlinear interactions

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We demonstrate for the first time that near plasmonic resonances the local field enhancement factor, which controls the efficiency of nonlinear interactions, can have a negative value, thus offering a new way of compensating losses in metamaterials.

Using a mode-locked femtosecond laser of only a few mW of average power and a metamaterial structure of asymmetrically split ring apertures in a 50 nm thick gold film we observed a resonant conversion of nonlinear absorption into nonlinear bleaching leading to a 12% increase of the metamaterial's transmission.

8423-51, Session 12

Magnetoelastic nonlinearity and conformational effects in metamaterials

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Current progress in nonlinear, tunable and active metamaterials [1] have been mostly inspired by engineering metamaterial elements with various nonlinear insertions which help to obtain the desired response on the level of individual elements. Recently, another approach was successfully implemented to achieve structural tunability [2] through deliberate adjustments in metamaterial lattice.

Now we report a novel step in metamaterials design, where mechanical properties of the structure are dynamically linked to electromagnetic response. By allowing an extra degree of freedom in the lattice, we obtain a nonlinear feedback: as soon as an incident electromagnetic wave excites the resonant elements, they are displaced from the original positions by the emerging attractive forces; this, however, alters the lattice constant and therefore shift the resonance as governed by the mutual interaction --- and then the electromagnetic excitations also changes. This provides a magnetoelastic behaviour [3] of the entire metamaterial, offering a complex pattern of nonlinear features.

Another way to use the electromagnetically induced forces is provided by a specific design of metamaterial elements [4]. We employ spiral particles which are at once electromagnetic resonators and mechanical springs. Interaction of electromagnetic radiation with such particles effectively changes their conformation, leading to nonlinear response and, in particular, nonlinear chirality. In addition to the magneto-mechanical coupling, this system is also prone to thermal effects, thus linking three different realms in physics.

We believe that our results open a new road in metamaterials design, and will lead to a number of useful applications for microwave, THz and optical ranges.

REFERENCES

[1] A.D. Boardman, V.V. Grimalsky, Yu.S. Kivshar, S.V. Koshevaya, M. Lapine, N.M. Litchinitser, V.N. Malnev, M. Noginov, Yu.G. Rapoport, and V.M. Shalaev, Active and tunable metamaterials, Laser Photonics Rev., 5, 287-307 (2011).

[2] M. Lapine, D.A. Powell, M.V. Gorkunov, I.V. Shadrivov, R. Marqués, and Yu.S. Kivshar, Structural tunability in metamaterials, Appl. Phys. Lett. 95, 084105 (2009).

[3] M. Lapine, I.V. Shadrivov, D.A. Powell, and Yu.S. Kivshar, Magnetoelastic metamaterials, Nature Materials, 11, 30-33 (2012).

[4] M. Lapine, I.V. Shadrivov, D.A. Powell, and Yu.S. Kivshar, Metamaterials with conformational nonlinearity, Scientific Reports, 1, 138 (2011).

8423-52, Session 12

Novel meta-surfaces to manipulate electromagnetic waves

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Meta-materials are man-made electromagnetic (EM) materials composed by subwavelength local resonance structures of electric and/or magnetic type, and thus possess arbitrary values of permittivity and permeability dictated by such resonance structures. Many novel EM properties, such as the negative refraction, the superlensing effect, and even the invisibility cloaking were predicted or discovered based on meta-materials. By carefully designing metamaterials with appropriate EM wave properties, one can employ metamaterials to efficiently manipulate various properties of EM waves, inlcuding the wave propagation, polarization, and so on. Here, we present our latest theoretical and experimental efforts in designing novel meta-surfaces (ultra-thin metamaterials) that can efficiently manipulate EM waves in various aspects.

We first experimentally demonstrate that a carefully designed meta-surface can trap photons for a long time, with measured effective wave speed ~ c/382 in a $lambda/27$ -thick microwave sample. The slow-wave effect is governed by the anomalous dispersion and surface plasmon excitations, which is more significant in thinner samples owing to stronger mode hybridizations. Light-matter interactions are remarkably enhanced inside the slow-wave structures, leading to perfect omni-directional light absorption and dramatically enhanced nonlinear generations, which are demonstrated by microwave experiments and full wave simulations. We next show that a particular inhomogeneous meta-surface can control the propagation direction of the EM wave reflected back from the meta-surface. Microwave experiments are performed to successfully verify the theoretical predictions, and the obtained results are in prefect agreements with full wave numerical simulations.

8423-53, Session 12

Magnetic metamaterials

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Fuelled by the promise for novel science and applications, research on metamaterial has expanded greatly over the past few years. This has included some explorations into the control of these new materials, but this has focussed mostly on changing the metamaterial dimensions and the shapes of the metamolecule units in the structure. We are exploring another method of control in microwave metamaterials, namely by closely coupling a metamaterial structure to soft magnetic materials. This is a novel technique where the natural resonance of the metamaterial interacts with the ferromagnetic resonance of the magnetic material. This hybrid interaction is then controllable through the application of an external DC magnetic field, thereby tuning the metamaterials response. In our experiments split ring resonator (SRR) metamolecules are fabricated on the underside of a coplanar waveguide transmission line providing the excitation for the system. An yttrium iron garnet (YIG) film, grown by pulsed laser ablation, is placed in close contact with the metamolecules. We have confirmed that the strong YIG-SRR coupling significantly modifies the microwave response; the frequency and lineshape of the SRR resonances can be controlled by the applied magnetic fields. We have investigated different SRR dimensions and compared the behaviour at frequencies close to the electrical and magnetic dipole resonances of the SRR structure.

8423-54, Session 12

Unravelling vector fields at the nanoscale

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One of the key properties of metamaterials is their unique response to the various components of both the magnetic and electric fields of light waves. The strong interplay between the geometry and the light results in highly structured light fields on the nanoscale.

In this presentation I will show recent progress in the visualization of such light fields beyond the diffraction limit. We show that light fields in the near field of fishnet structures are highly structured. We use dedicated near-field probe geometries to home in on individual vector components of either the electric or (for the first time) the magnetic component of confined light fields.

In certain instances the probe can go beyond its role as “innocent observer” and actually perturb the properties of a (high-Q) structure. We show that, in this way, we can induce a diamagnetic light-matter interaction.

8423-55, Session 12

Concentrator of magnetic field of light

P. Wróbel, Univ. of Warsaw (Poland); T. J. Antosiewicz, Chalmers Univ. of Technology (Sweden); T. Szoplik, Univ. of Warsaw (Poland)

In the recent decade metamaterials with magnetic permeability different than unity and an unusual response to the magnetic field of incident light were developed [e.g. 1]. Existence of metamaterials created an interest in a scanning near-field magnetic microscope for studies of magnetic responses of their subwavelength elementary cells [2-5]. We present a method of measuring magnetic responses of elementary cells within a wide range of optical frequencies with single probes of two types. The first probe is made of a tapered silica fiber with radial metal stripes separated by equidistant slits of constant angular width [4]. The second probe is similar to a metal coated, corrugated, tapered fiber aperture SNOM probe, but in this case corrugations are radially oriented. Both probes have internal illumination with azimuthally polarized light. In the near-field they concentrate into a subwavelength spot the longitudinal magnetic field component which is stronger than the transverse electric one. Of the two types of probes, the former has larger throughput, however, at the expense of a larger full-width at half-maximum (FWHM) of the focus. The latter, due to a full coating, has worse energy efficiency, but a smaller FWHM and better ratio of the magnetic-to-electric energy densities in the focal spot.

1. W.T. Chen, C.J. Chen, P.C. Wu, S. Sun, L. Zhou, G.-Y. Guo, C.T. Hsiao, K.-Y. Yang, N.I. Zheludev, D.P. Tsai, Opt. Express 19, 12837 (2011).

2. M. Burresi, D. Van Oosten, T. Kampfrath, H. Schoenmaker, R. Heideman, A. Leinse, L. Kuipers, Science 326, 550 (2009).

3. S. Vignolini, F. Intonti, F. Riboli, L. Balet, L.H. Li, M. Francardi, A. Gerardino, A. Fiore, D.S. Wiersma, M. Gurioli, Phys. Rev. Lett. 105, 123902 (2010).

4 T.J. Antosiewicz, P. Wróbel, T. Szoplik, Opt. Express 18, 25906 (2010).

5. J.S. Lee, S. Han, J. Shirdel, S. Koo, D. Sadiq, C. Lienau, N. Park, Opt. Express 19, 12342 (2011).

8423-91, Session 12

Magnetic light-matter interactions: quantifying and exploiting magnetic dipole transitions

R. Zia, Brown Univ. (United States)

Although it is often assumed that all light-matter interactions at optical frequencies are mediated by electric dipole transitions, strong optical frequency magnetic dipoles do exist. In fact, we see magnetic dipole emission every day from the lanthanide ions that illuminate everything from fluorescent lighting to telecom fiber amplifiers. However, most applications have overlooked the device implications of magnetic transitions throughout the visible and near-infrared regime.

Here, we will illustrate how the naturally occurring magnetic dipole transitions of lanthanide ions provide both a new way to probe magnetic light-matter interactions and a new degree of design freedom for active photonic devices. Specifically, we will demonstrate how the different symmetries of electric and magnetic dipoles can be exploited to identify, quantify, and control light emission, even at sub-lifetime scales.

Despite similar radiation patterns, magnetic and electric dipole emitters have different symmetries with respect to polarization and phase. Thus, in an inhomogeneous environment, we can tailor interference effects and the local density of optical states to selectively enhance either electric or magnetic dipole emission.

First, we will present quantum mechanical calculations to identify all magnetic dipole emission lines in the trivalent lanthanide series. These calculations highlight the importance of magnetic dipole emission on mixed transitions, such as the 1550nm emission from trivalent erbium (Er3+). Next, we will present a novel spectroscopy technique to directly quantify the electric and magnetic dipole contributions from any mixed transition. These measurements have allowed us to directly quantify the intrinsic spontaneous emission rate (Einstein A coefficient) at each wavelength, and to directly map both the electric and the magnetic local density of optical states. Finally, using the spectrally-distinct electric and magnetic transitions of trivalent europium (Eu3+), we illustrate how self-interference can be used to dynamic spectral tuning at sub-lifetime-scales.

8424-01, Session 1

Optical spectroscopy of single molecules and gold nanoparticles

M. Orrit, Leiden Univ. (Netherlands)

Far-field optical selection of individual molecules or nanoparticles has specific advantages. Laser excitation is non-invasive, can reach much beyond surface layers, and commands a wide range of time-resolved and frequency-resolved techniques. Optical signals provide unique insights into the dynamics of nano-objects [1], as illustrated by recent topics from our group.

i) In our study of single gold nanoparticles by photothermal and pump-probe microscopy, we detect acoustic oscillations launched by a pump pulse [2]. Individual gold nanoparticles can be used for local plasmonic, mechanical and chemical probing. An optical trap for gold particles allows us to eliminate perturbation by a substrate [3].

ii) We probed the glass transition in supercooled glycerol [4] by following rotational diffusion of single fluorescent molecules. We found large differences in local viscosity, with exceedingly long memory times (days), and attribute heterogeneity to solid-like structures.

iii) Photothermal microscopy opens the study of non-fluorescent absorbers such as molecular aggregates or conjugated polymers, down to the single-molecule level [5]. It can provide new insight into complex relaxation phenomena, such as blinking.

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References:

1. F. Kulzer et al., Angew. Chem. 49 (2010) 854.
2. A. L. Tchebotareva et al., Laser Photon. Rev. 4 (2010) 581-597.
3. P. V. Ruijgrok et al., Phys. Rev. Lett. 107 (2011) 037401.
4. R. Zondervan et al., Proc. Nat. Acad. Sci. USA 104, 12628 (2007).
5. A. Gaiduk et al. Science 330 (2010) 353.

8424-02, Session 1

Metal nano-particle affected optical and transport properties of molecular complexes

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It is of particular interest in plasmonics to achieve a detailed understanding of molecule metal-nanoparticle (MNP) interactions and MNP affected transport and optical properties. To attain this goal a microscopic theory is introduced which focuses on systems with a small spatial extension where the molecule-MNP interaction is dominated by its (instantaneous) Coulomb part.

As a first application MNP affected intermolecular excitation energy transfer is considered. Then, emission and absorption spectra of molecular complexes placed in the proximity of a spherical MNP are discussed. A particular application focuses on chromophore complexes formed by a butanediamine dendrimer to which pheophorbide-a molecules are covalently linked. To achieve a description with atomic resolution and to account for the effect of an ethanol solvent a mixed quantum classical methodology is utilized. Spectra of linear absorbance influenced by a MNP and spectra of transient anisotropy showing signatures of excitation energy transfer are presented.

8424-03, Session 1

Single particle spectroscopy of twisted gold bipyramids correlated with TEM and TEM 3D

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The optical properties of noble metal nanoparticles (NPs) are known to be dominated by the localized surface plasmon resonance (SPR) and depend on size, shape and also environment of the nano-objects. Those properties, as extinction or scattering, can be considered as fingerprints for biosensing or chemical reactivity control. To use nanoparticles as nanosensor, (i) suitable optical set-up to characterize quantitatively their optical response and (ii) monodisperse solutions of nanoparticles with high optical response are required. Here we present optical results on twisted bipyramids obtained by Spatial Modulation Spectroscopy (SMS).

First, we present a broadband high sensitive technique based on SMS, allowing absolute extinction and quantitative scattering measurements on a single nanoparticle on the same set-up [1]. Moreover, this optical technique can be coupled by the transmission electron microscopy (TEM), classical and in 3D, to correlate the exact morphology of nanoparticles with their optical response [2].

Then the optical response of gold twisted bipyramids is investigated by extinction and scattering spectroscopy. The bipyramids are synthesized by an original chemical seed mediated growth process in high yield [3]. The gold bipyramids are studied in polarisation. With a longitudinal excitation, we observe a strong resonance red shifted around 750 nm, depending on the size of nanoparticles.

These results are also compared to the theory using COMSOL software and their optical response to the one obtained with nanorods for sensing application.

[1] P. Billaud, S. Marhaba, N. Grillet, et al., Review of Scientific Instruments 81, 043101 (2010).

[2] P. Billaud, S. Marhaba, E. Cottancin, et al., J. Phys. Chem. C 112, 978 (2008).

[3] J.R.G. Navarro, D. Manchon, F. Lerouge, et al, submitted.

8424-04, Session 1

Anomalous lifetime effects in fluorescence resonance energy transfer (FRET)

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Fluorescence resonance energy transfer (FRET) is a major tool in Cell Biophysics and Biochemistry. FRET involves the transfer of energy between electronically excited donor and acceptor molecular "tags" that are either attached to the different locations within a protein (intramolecular FRET) or to different proteins (intermolecular FRET) allowing the measurement of conformational changes and intermolecular associations (complex formation) respectively. FRET is most directly detected by the measurement of fluorescence lifetime changes. The most common approach is to measure the shortening of the donor fluorescence lifetime as a result of energy transfer. Although widely used, FRET signals are sometimes hard to interpret, in part due to the presence of a large fraction of non-interacting donor and acceptor species. Recent work by us has shown that measurement of the rise and subsequent decay of the directly transferred (sensitised) fluorescence emitted by the acceptor as a result of FRET provides a far clearer measurement of the FRET rate under these conditions. Using this approach we have recently demonstrated that the in vivo regulation of 3-phosphoinositide dependent protein kinase 1 (PDK1) a key protein involved in cell signalling proceeds by homodimerisation [1].

FRET signals can in principle provide precise distance and angular information on protein-protein interactions and conformational change provided fluorescence lifetime and fluorescence anisotropy (polarisation) measurements are combined.

A combined anisotropy and intensity analysis of the single-photon sensitized fluorescence observed in the PDK1 system (EGFP donor and m-Cherry acceptor) indicates that the excited state lifetime of the acceptor is longer than that resulting from direct optical excitation. Such behaviour is not expected in weak dipole-dipole coupling. Reasons for this apparently anomalous behaviour are discussed.

[1] T A. Masters, V Calleja, D. A. Armoogum, R. J. Marsh, C. J. Applebee, M. Laguerre, A. J. Bain and B. Larijani, Science Signaling 3 (145), ra78. (26 October 2010)

8424-05, Session 1

In situ optical monitoring of the plasmon resonance of Ag nanoparticles submitted to oxidation or/and etching

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In situ surface differential reflectance spectroscopy is used to monitor the minute changes in surface plasmon resonance (SPR) of silver nanoparticles (NPs) synthesized by magnetron sputtering. The sharp absorption of light in the visible range due to this SPR is sensitive to both the morphology and organization of the silver NPs, and to the chemical atmosphere surrounding them. Post mortem analyses (transmission electron microscopy, X-ray scattering) enables to access the nanostructures while the in situ optical spectroscopy allows detecting all physical or chemical effects on the NPs and estimating the kinetics.

Specifically to magnetron sputtering, the NPs can be exposed to partially ionized oxygen (O2(+)) or/and to Ar bias plasma. O2(+) exposure induces an important increase of both the NP size and the interparticle distance that could be explained by Ostwald ripening or migration and coalescence. The SPR is red-shifted and damped up to its complete disappearance suggesting strong chemical interactions between O2(+) species and the Ag NPs as well as broad size and shape distributions. On the contrary, bias plasma treatment induces a decrease of both the NP size and the interparticle distance due to sputtering/redeposition effects along with an increase of the NP aspect ratio (height / in-plane diameter). The SPR is blue-shifted (shape effect) and damped (size effect).

Finally, silver NPs are exposed to oxidation/etching cycles. The SPR is first completely suppressed under O2(+) exposure and then reappears under plasma annealing, suggesting the removal of the oxide species encapsulating pure silver NPs. Capping the oxidized NPs by a thin (1 nm) dielectric (Si3N4) layer is an alternative - but less efficient - way to enable the SPR reappearance by causing the oxygen desorption.

8424-06, Session 2

Dielectric loaded surface plasmon waveguides for datacom applications

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Dielectric loaded surface plasmon polariton waveguides (DLSPPW) are comprised of a dielectric strip (polymer) deposited on a metal layer. The typical cross-section of DLSPP waveguides for single-mode operation is in the range of 500x500nm2 and the propagation distance of the SPP mode traveling at the metal/polymer interface is around 40-50 µm at telecom frequencies. These properties make the DLSPP waveguides good candidates for the development of SPP-based optical components such as filters, directional couplers, resonators, multi-modes or Mach-Zehnder interferometers (MZI).

The results we discuss in this contribution have been obtained in the framework of the European project PLATON targeting specifically the merging of silicon photonics and plasmonics components exploiting DLSPP waveguides for routing a Tb/s signal. The routing is obtained by exploiting the large thermo-optic coefficient of the polymer in the DLSPPW.

In the first part of this contribution, we will describe different types of thermo-optical DLSPPW based switches exploiting either ring resonator configurations or dual-mode interferometer designs. The principle of each of these configurations will be first reviewed. For ring resonators switches, the influence of the opto-geometrical parameters onto the performances of the devices will be discussed. While, ring resonators switches exploit single-mode plasmonic waveguides, we will show that dual mode interferometer supporting simultaneously a plasmonic mode and a photonic mode can be very efficient to achieve optical switching over a short propagation distance.

From an experimental point of view, the performances of the switches will be evaluated using either radiation leakage microscopy in the DC regime but also a fiber-to-fiber characterization in the dynamic regime. The fiber-to-fiber characterization of short propagation distance waveguided modes can be performed only using a specific illumination configuration. We will describe this specific configuration along with the optical properties of the modes involved in the excitation of the DLSPP waveguides. By operating a 10 Gb/s telecom signal transmission along straight DLSPPWs, we will show that our fiber-to-fiber approach offers an efficient and easy-to-implement way to interface DLSPPW components to the rest of the optical world.

The second part of this contribution will be dedicated to the description of a new detection scheme of propagating surface plasmon polariton (SPP) mode relying onto a thermo-electric effect. In this scheme, the surface plasmon waveguide is not only used as a waveguide but also as an electrode of a thermo-couple. By monitoring the voltage existing between the SPP waveguide and a second electrode, we will show that it is possible to measure the power travelling along the plasmonic waveguide. Unlike other configurations using any type of photo-detectors, we will show that our detection scheme operates without picking any useful power.

8424-07, Session 2

High efficient broadband nano-plasmonic coupler for directional control of light propagation in a photonic waveguide

T. Sidiropoulos, S. A. Maier, R. F. Oulton, Imperial College London (United Kingdom)

We report efficient broadband coupling of free-space radiation into a semiconductor waveguide via a Localised Surface Plasmon (LSP) resonance. The proposed plasmonic coupling element consists of gold nano-particles placed in the vicinity of a photonic Silicon waveguide. This approach uses the advantages of plasmonic nano-particles, namely strong light-matter interactions and compactness, while avoiding their high loss by radiating rapidly into a low loss photonic mode. Numerical simulations show coupling efficiencies into each direction of 13% for a single particle and 20% for an identical particle pair, near the telecoms wavelength, $\lambda \approx 1.55$ µm. By varying the length of one particle, we also explore the use of relative phase between LSPs to control the coupling direction. While complete cancellation of coupling into one direction is achievable with a pi/2 phase difference, coupling into the other direction is not enhanced. However, the coupling between LSPs and the waveguide mode is sufficiently strong that multiple scattering can increase the coupling efficiency to 28% into one direction for much smaller phase differences. Our results are in general agreement with a coupled oscillator model, which also identifies how the coupling can be improved. Such plasmonic coupling elements are considerably more compact than grating couplers yet provide comparable efficiency over a much broader spectrum. Thus, they are a viable coupling alternative for integrated semiconductor photonics technology.

8424-08, Session 2

Interference of ultrashort surface plasmon polaritons: double slits, plasmonic cavities, and propagation tracking

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We present studies on surface plasmon-polariton (SPP) interference effects in systems with multiple coherently excited SPP beams. Replica of a laser beam used for excitation of SPPs is realized using Michelson-interferometers. The SPPs on thin metallic films are excited by local scattering of the laser light on laser fabricated surface nanostructures, consisting of polymeric ridges [1]. SPP interference and scattering effects are investigated by leakage radiation microscopy [2]. The experimental arrangement allows resembling the well known Young's double slit experiment in its plasmonic form, and possibilities for plasmonic quantum erasers are discussed in this context. Two parallel straight or curved ridges are shown to operate as a cavity for SPPs, where the controllable phase difference allows concentrating the SPP energy in the local region between the ridges. The interference of SPPs inside dielectrically-loaded SPP waveguides [3] as well as the interference of SPPs with additional light fields is employed for tracking the propagation of ultrashort SPP pulses excited by 50 fs laser pulses at a central wavelength of 800 nm. We present first- and second-order autocorrelation of the plasmon fields, allowing measuring SPP dispersion and pulse durations. The experimental results are supported by theoretical modelling using the Green's tensor approach and FDTD simulations.

References:

1) C. Reinhardt et al., "Laser-fabricated dielectric optical components for surface plasmon polaritons", Optics Letters 31, pp. 1307-1309 (2006);

2) C. Reinhardt et al., "Rapid laser protoyping of plasmonic components", Applied Physics A 89, pp. 321-325 (2007);

3) C. Reinhardt et al., "Direct laser-writing of dielectric-loaded surface plasmon-polariton waveguides for the visible and near infrared", Appl. Phys. A 100, pp. 347-352 (2010)

8424-09, Session 2

Surface plasmon coupled emission in highly directional and sensitive plasmonic devices

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In our experiments, four different pitches, including 400 nm, 500 nm, 600 nm and 800 nm, were adopted for the one-dimensional lamellar grating devices. They were grating devices with 1-D pattern an exposure area of 1.2×1.2 mm2 fabricated by Electron-Beam Lithography system.

We have to modify our experimental design of decreasing Au thin film thickness, it became more pronounced in the 20 nm Au film at the pitch of 600 nm structure. In this study, the emission filtering is enabled by evanescent wave coupling across the upper layer metal film. In this way, we can probe the response of the SPGCE system when the two modes are brought into resonance.

The experimeantal and theoretical results showed that SPGCE at different pitch can match a linear shifting of momentum (K) of about 4.8 μm-1 per 100 nm pitch size with 4 times enhanced intensity. The SPGCE of active Alq3 molecules through the metal showed different wavelengths at different angles. It suggests that the reciprocal interactions of optical absorption and scattering due to active emission of Alq3 and grating metal nanostructures can result in the tuning of color gamut as well as the direction of emission.

8424-10, Session 2

Nanoantenna structures for strong coupling studies of surface plasmon polaritons and quantum dots

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We briefly describe our results on planar metal film - quantum dot samples at the limit of high field intensities. We then present measurement and simulation results on nanoantenna structures fabricated with electron beam lithography. Such structures offer interesting possibilities to study strong coupling phenomena between surface plasmon polaritons (SPP) and, e.g., quantum dots, along the lines of our previous work on vacuum Rabi splitting for SPP and dye molecules [1,2,3].

[1] T.K. Hakala, J.J. Toppari, A. Kuzyk, M. Pettersson, H. Tikkanen, H. Kunttu, and P. Törmä, Vacuum Rabi splitting and strong coupling dynamics for surface plasmon polaritons and Rhodamine 6G molecules, Phys. Rev. Lett. 103, 053602 (2009)

[2] R.J. Moerland, T.K. Hakala, A.I. Väkeväinen, A.-P. Eskelinen, G. Sharma, J.J. Toppari, A. Kuzyk, M. Pettersson, H. Kunttu, and P. Törmä, Vacuum Rabi splitting for surface plasmon polaritons and Rhodamine 6G molecules, Metamaterials VI, Eds. V. Kuzmiak, P. Markos, T. Szoplik, Proc. of SPIE2011 Vol. 8070, 80700D (2011)

[3] R.J. Moerland, G. Sharma, A.I. Väkeväinen, A.-P. Eskelinen, H.T. Rekola, and P. Törmä, From vacuum Rabi splitting towards stimulated emission with surface plasmon polaritons, Proc. SPIE 8096, 809606 (2011)

8424-127, Session 2

Optical properties of isolated and arrayed hollow nanotriangles

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Arrays of metallic nanostructures are very promising building elements in biochemical sensing, Surface Enhanced Raman Spectroscopy (SERS) and many other applications due to their controllable scattering and absorption properties and strong local electromagnetic field confinement and enhancement. This paper studies silver (Ag) hollow nanotriangles (HNTs) on a quartz (SiO2) substrate in comparison with solid nanotriangles (SNTs) on their optical spectra and near-field electric field distributions. Influences of geometrical parameters on the extinction spectrum of an isolated and arrayed HNT are computed with finite difference time domain (FDTD) method. The optimum geometry for a distinguished resonance feature in visible wavelength range is determined and a high value figure of merit (FOM) of the particular spectral peak is obtained based on the optimum HNT geometry.

For an HNT array with a series pitches, the dipole mode is suppressed and the tripole mode is split into two peaks due to the coupling among adjacent HNTs. Consequently the FOM values of these peaks are further increased comparing with that of an isolated HNT.

Using E-beam lithography (EBL) method to pattern nanotriangles on a silver film with the thickness of 60 nm on a quartz substrate, we have fabricated HNT arrays with side lengths of 100, 150 and 200 nm and various ring widths from 20 to 50 nm. For isolated HNTs, the pitch is set as 4 m, while for HNT arrays with different side lengths, the gaps in between adjacent HNTs are varied from 15 to 100 nm. The scattering and transmission spectra from individual nanotriangles have been measured by using an implemented dark field microscopic and broad band spectroscopic platform. The spectra from both isolated and arrayed HNTs agree considerably well with the simulation results obtained with FDTD method. Trends of spectral variation caused by geometric changes are also proved from experiments.

8424-11, Session 3

Quantum-dot Mollow triplet in a semiconductor cavity-QED system

S. Hughes, Queen's Univ. (Canada)

No abstract available

8424-12, Session 3

Controlling the interaction of photons and single quantum systems in an optical microresonator

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Small optical micro-resonators are structures which confine light to volumes with dimensions on the order of one wavelength and provide an important means for controlling light-matter interaction in integrated optics. In the ultimate limit, the miniaturization of laser light generation is a single quantum system enclosed in an optical micro-resonator.

Here we would like to present our work on the study of the interaction of single quantum emitters or nanoparticles located in the confined optical field of a single-mode micro-resonator formed by two silver mirrors enclosing a transparent dielectric medium. The quantum system is excited by a well-defined field distribution formed between the mirrors by placing the resonator into the focus of a high NA microscope objective. Using a radially or azimuthally polarized laser beam for excitation, the longitudinal position and the 3D orientation of the transition dipole moment of a single quantum system can be determined by scanning the resonator through the focal volume. The geometric configuration of the emitter in the cavity has a large effect on the coupling of radiation to the modes the resonator, leading to a spectral confinement of the broadband fluorescence. By precisely controlling the mirror separation, the cavity resonance can be tuned, sculpting the photonic environment surrounding the emitter. In this fashion, influence can be taken on the relaxation path of excited quantum systems: while the resonator has no effect on an emitter's nonradiative decay, the balance with its radiative decay channels can be shifted by modifying the local density of optical states, allowing determination of a process's quantum yield. Using pulsed excitation, we gain additional insight into the dynamics of an emitter's decay path. The spectral response of the microcavity can be narrowed considerably by coupling it to an external resonator, allowing the selective observation of single narrow-band emitters.

8424-13, Session 3

Quantum plasmonics: nonlinear effects and field enhancement in a plasmonic nanoparticle dimer

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A fully quantum mechanical investigation reveals that the optical properties of a coupled metallic nanoparticle dimer can exhibit strong nonlinear effects. The time-dependent density functional approach is used to calculate both the plasmon energies and field enhancements in the junction between the two nanoparticles as a function of the interparticle spacing and of the power of the incident light. We show that both classical as well as linear quantum mechanical descriptions of the system fail even for moderate incident light intensities.

The nonlinear discharge current between the two nanoparticles tends to neutralize the plasmon-induced surface charge densities on the opposite sides of the junction. This effect reduces the coupling between the two nanoparticles and the field enhancement compared to linear theory. A substantial nonlinear effect is revealed already at incident powers of 10^9 W/cm^2 for interparticle separation distances as large as 1 nm and down to the touching limit.

8424-14, Session 3

Strong second-harmonic generation from silicon nitride films and resonant waveguide gratings

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Silicon nitride (SiNx) is an important material for on-chip waveguides and resonators due to its large refractive index and low optical loss at the visible and near-infrared wavelengths. In this work, we report our results on second-harmonic generation (SHG) from the SiNx thin films and resonant-waveguide gratings (RWGs) at the fundamental wavelength 1064 nm. The SiNx thin films with the thicknesses between 100 nm and 1500 nm were prepared on fused silica substrates by plasma enhanced chemical vapor deposition. The second-order properties of the samples were characterized by second-harmonic generation as a function of the state of polarization of the fundamental field and as a function of the angle of incidence. The absolute signal levels from the thin films were significantly higher than those from typical dielectric surfaces. The dependence of the film thickness was as expected for a bulk response, but the origin of the possible bulk response remains unknown. Sub-wavelength RWGs based on the SiNx films were prepared by the UV-nanoimprint lithography and etching techniques. Giant enhancement of SHG was observed at the resonant angle of the optimized RWGs structure. The enhancement factor, i.e., the comparison of the SHG intensity from the SiNx RWGs and a flat SiNx film with the same thickness measured under its optimum condition, was determined to be about 1000. The strong second-order nonlinear response from the SiNx films and RWGs has great potential applications in the on-chip nanophotonic devices.

8424-15, Session 3

Nonpeturbative cavity-QED using a quantum dot and a single metal nanoparticle

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The route to photonic vacuum engineering (e.g., via cavity-QED) traditionally employs a lossless dielectric cavity system, exploiting an optical mode with a suitably large quality factor, Q, and small effective mode volume, V. The local photon density of states (LDOS) scales proportionally with Q/V. Dielectric microcavities including photonic crystals and micropillars have shown remarkable successes in quantum optics, but the lower limit on V in such systems is set by diffraction. Additionally, the narrowband resonance associated with high Q requires very narrow quantum-dot exciton linewidths, only achievable at low temperatures. In an effort to further increase the LDOS and decrease the system size to sub-wavelength dimensions, it can be advantageous to examine plasmonic systems where light is confined to the surface of a metal and decays evanescently from its surface. From a quantum optics

perspective, dot-metal coupling presents a major challenge in in the theoretical formalisms because of intrinsic losses.

In this work, we investigate the quantum optical properties of a single photon emitter near the surface (but outside the regime of electronic tunnelling) of a metal nanoparticle using a photon Green function technique that rigorously quantizes the electromagnetic fields. We predict Purcell factors of up to 50,000 due to higher-order plasmon modes for both a 7-nm and 20-nm radius metal nanoparticle, and show the drastic failure of employing a dipole approximation in regimes where nonperturbative quantum optical interactions occur; we also calculate enormous photonic Lamb shifts of around 40 meV. Considering a small quantum-dot, we demonstrate that the strong coupling regime should be clearly observable in the far-field emission spectrum, even at room temperature and despite the non-propagating nature of the higher order modes. The vacuum Rabi doublet becomes a rich spectral quartet with two of the four peaks anticrossing, and surviving in spite of significant non-radiative decays.

8424-61, Poster Session

Generation of entangled photons by excited two-level supercold atom in high finesse nanocavity with single decaying resonance mode

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The exact theory of generating the “entangled photons” by excited motionless two level atom in one-dimensional high finesse nanocavity with a single resonance linearly polarized mode, decaying at the average rate Γ, is presented. We have studied the resonance emission out of the macromolecule-like system “nanocavity with resonance mode and excited atom” in area $0 \leq \Gamma \leq 0.2g$,with g being coupling constant for electro dipolar interaction, The entangled photon’s properties were investigated by using the Schrödinger equation solution, obtained by us with using Green functions formalism. The entangled photon consists of two anti-phase ($\omega a \pm g$)-components with average total energy equal to 1/2( ) = ωa –atomic frequency. We have revealed that the arising of the entangled photons at the outlet of nanocavity occurs as a result of disintegration of metastable interference superpositional field structure, ejected out of the cavity through the partly transparent mirror. This structure is produced by the self-consistent AC Stark effect, created by electric fields of rotating atomic dipole and the resonance mode. The field splits atomic levels and radiation transitions among them, producing in the nanocavity the ($\omega a \pm g$)- photons. Since the rate of mode damping $\Gamma << g$ frequencies of those photons drop out of the Lorenz-shaped packet of quasi-modes. So probability to occupy by those photons own spectral places within cavity is very small. So they form in the cavity the superposional interference structure, consisting of the carring ωa - mode wave modulated with frequency 2g. The profiles of ($\omega a \pm g$)-components have identical form exp(– t Γ)t Γ, with average lifetime in cavity estimated to be 4ln Γ/Γ. The 3D plots of disintegration process give the value ≈ 500/g.

8424-62, Poster Session

Dynamic light scattering study of mixture PEG with the AOT microemulsion

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Dynamic light scattering is used for study the interaction of PEG with AOT microemulsion. The correlation function as a function of delay time shows a single strength exponential for AOT microemulsion with and without PEG. With increase of PEG concentration the delay time is increasing and also shape of correlation function is changing that describe the polydispersity increase with increase of concentration of PEG. In this work, the collective diffusion coefficient is constructing from the correlation function as a function of delay time for the AOT microemulsion mixed with different concentration of PEG. Our results shows increase of PEG concentration slowing down the dynamic of systems.

8424-63, Poster Session

Real-space distribution of cavity modes in single ZnO nanowires

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Scanning near-field optical microscopy (SNOM) has become nowadays a very powerful technique for investigating the optical properties of nanostructures with a sub-wavelength spatial resolution below 100 nm, such as waveguiding effects in ZnO nanowires (NWs). A spatially resolved study of the electromagnetic field distributions of different cavity modes in ZnO NWs is still lacking. In this work, we have used a near-field optical microscope to map out the evanescent fields of optically excited single-crystal ZnO NWs grown on quartz substrates by the vapour transport method using Au as catalyst. The SNOM measurements were performed at room temperature in transmission-collection mode using four different laser wavelengths (378, 514, 633 and 785 nm). They reveal a different spatial distribution of the electromagnetic fields associated to each cavity mode, which are unique properties of the NWs depending primarily on their size and the wavelength of the mode. The SNOM patterns are quite different. Whereas for UV illumination the pattern exhibits two well defined bright lines running along the edges of the upper hexagonal facet of the wire, for red laser excitation the SNOM pattern displays a strong but wider maximum at the center of the facet. The latter also exhibits a periodic modulation of the near-field intensity all along the axis of the wire. In order to interpret the experimental findings, we have performed electrodynamics simulations using the discrete dipole approximation (DDA), which is an accurate numerical method in which the object of interest is represented as a cubic lattice of N polarizable points. We used about 890000 dipoles to describe the ZnO NW, out of a total of 1.5 million for taking also the substrate into account. The DDA plots represent the field distribution in cross section of a hexagonal wire supported by a quartz substrate on one of its facets and with true dimensions, as obtained from the topography SNOM profiles. The false color scale corresponds to the field intensity normalized to that of the incident light. For clarity we only show the field intensity outside the wire, for this is the magnitude sensed by the SNOM probe. We notice the striking qualitative agreement between calculated and measured field distributions.

8424-64, Poster Session

Description of undamped surface plasmon-polariton collective mode in metallic nanochain within nonlinear approach

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We present an analysis of collective surface plasmon excitation propagating in long (infinite for the model) nano-chain of metallic nano-spheres coupled in near field of plasmonic oscillations including all forms of plasmon energy dissipation. The particular attention is paid to plasmon damping due to Lorentz friction. Previously we have identified an unstable mode of surface plasmon excitations coupled due to near field energy transfer with relativistic retardation in the system of nanometer scale gold spheres ordered into chain also with nanometer-scale separations [Jacak W., Krasnyj J., Jacak J., Chepok A., Jacak L., Donderowicz W., Hu D. Z., Schaadt D. M., 2010, Undamped collective surface plasmon oscillations along metallic nanosphere chains, J. Appl. Phys. 108, 084304]. This mode was, however, described within a

linear theory. To stabilize this undamped collective mode, the nonlinear corrections are needed to be included and the appropriate nonlinear theory formulation we now present. This leads to stabilization of the mode but with a fixed amplitude and vanishing attenuation. This special mode would of particular convenience for arrangement of sub-diffraction plasmon circuits. The undamped mode would be responsible for long range propagating plasmon-polariton modes in metallic nano-chains observed experimentally by Atwater group at Caltech.

8424-65, Poster Session

The design and optimization of three-wavelength wavelength division multiplexing based on photonic crystal waveguides

P. Liang, China Jiliang Univ. (China)

A new type three-wavelength wavelength division multiplexing based on two dimension photonic crystals is designed according to the theory of coupling and decoupling. The finite-difference time-domain method is used to simulate the efficiency of the device, and the simulated results show that higher transmittance is achieved by adjusting the size of dielectric rods in the coupling region. The present device not only has a higher transmission rate, but also has a smaller size which is only 23 μm × 9 μm .

8424-66, Poster Session

Improving the performance of white light emitting diode by using dielectric film technique

L. Wang, China Jiliang Univ. (China)

High efficiency white light emitting diodes based on ultraviolet (UV) LED with blue and yellow phosphor are proposed by using dielectric film. The dielectric film consisting of alternating layers of HfO_2 and SiO_2 is added between phosphor layer and sapphire substrate of the LEDs. Monte Carlo simulations and theoretical analysis for this design show that the light efficiency is enhanced by 8% and the correlated color temperature is also improved. These are attributed to reflecting upward the back-scattered blue and yellow light from the phosphor layer.

8424-67, Poster Session

Optimizing magneto-optical activity and optical losses by electromagnetic field engineering in metal-dielectric magnetoplasmonic nanodiscs

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The phenomenology associated to systems where plasmonic and MO properties coexist has recently become an active area of investigation. In the so called magnetoplasmonic structures, magnetic and plasmonic properties are intertwined, allowing for example plasmonic properties to become tunable upon the application of a magnetic field (active plasmonics), or the MO effects to be largely increased by plasmon resonance excitation, as a consequence of the enhancement of the electromagnetic (EM) field in the MO active component of the structure.

The study of the enhanced MO activity in structures with subwavelength dimensions is especially interesting since they may be viewed as nanoantennas in the visible range with MO functionalities. The light harvesting properties of these systems upon plasmon resonance excitation bring as a consequence an enhanced EM field in its interior, and more interestingly in the region where the MO active component is present. At this stage, optimizing the EM field distribution within the structure by maximizing it in the MO components region while simultaneously minimizing it in all the other, non MO active, lossy components, will allow for the development of novel systems with even larger MO activity with reduced optical losses, becoming an alternative to state of the art dielectric MO materials, like garnets.

In our work we will show how the insertion of a dielectric layer in Au/Co/Au magnetoplasmonic nanodisks fabricated by colloidal hole lithography induces EM field redistribution in such a way to concentrate it in the MO active layer (Co) reducing it in the other elements. The obtained system exhibits large MO activity and low optical extinction in the high wavelength range (around 780 nm).

References:

J.B.Gonzalez-Diaz, et al. Plasmonic Au/Co/Au nanosandwiches with enhanced magneto-optical activity. Small, 4 (2008) 202.

V.V.Temnov, et al., Active magnetoplasmonics in hybrid metal/ferromagnet/metal microinterferometers. Nature Photonics, 4 (2010) 107.

A.Dmitriev et al., Gold-silica-gold nanosandwiches: tunable bimodal plasmonic resonators. Small, 3 (2007) 294.

D.Meneses-Rodríguez, et al., Probing the Electromagnetic Field Distribution within a Metallic Nanodisk. Small, in press (2011). DOI: 10.1002/smll.201101060

8424-68, Poster Session

Triggering a photochromic ring-openig reaction of spiropyran derivative by excitation rare earth doped luminescent nanocrystals

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It was found that excitation of fluoride ($NaYF_4$) nanocrystals (NCs) doped with the Eu^{3+}rare earth ions at 20% [1] may be used to drive the photochromic conversion of spiropyran [2].

Inducing the photochromic reaction by an energy transfer was studied in a hybrid material produced by mixing of the nanocrystals and the photochromic compound into polymethylmethacrylate (PMMA) matrix. The obtained system exhibits both fluorescence and photochromic properties. The photodriven ring opening reaction (PhOp) is induced by the UV light λ_{PhOp}= 365 nm, and the photodriven ring closing (PhCl) reaction is usually induced by green light at λ_{PhCl}= 550 nm. By excitation at $\lambda_{exc.}$= 394 nm, NCs emit fluorescence, peaking at $\lambda_{em.}$= 590 nm and $\lambda_{em.}$= 610 nm. In hybrid materials, such an excitation leads also to an efficient PhCl reaction of the opened form of the photochromic species. Experiments involved the kinetics measurement of the PhOp and PhCl reactions using UV/Vis spectroscopy, and the fluorescence quenching in the hybrid material. The photochromic kinetics did not obey a first-order reaction rate. To describe the process, an improved differential equation was used [3].

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Literature:

1. J. Olesiak-Banska, M. Nyk, D. Kaczmarek, K. Matczyszyn, K. Pawlik, M. Samoc, Optical Materials, 33, (2011), 1419.

2. S. Bénard, P. Yu, Advanced Materials, 12, (2000), 48.

3. R. Metivier, S. Badre, R. Meallet-Renault, P. Yu, R. B.Pansu, K. Nakatani , J. Phys. Chem. C, 113 (27), (2009), 11916.

8424-69, Poster Session

Periodic nanogap arrays for Raman and fluorescence enhancement: modeling and performance

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We will discuss the use of dense periodic nanogap arrays for plasmonic sensing applications. A high-throughput and well controlled fabrication process will be presented, that can yield nanogap arrays over mm2 large areas with periodicities above 150 nm and a high nanogap accuracy of ±1.5 nm. Extreme ultraviolet interference lithography (EUV-IL) was used to provide 1D line arrays or 2D dot arrays on the substrate, which was typically float glass or silicon. Angular evaporation was then utilized to evaporate metal, typically Au and Ag, directly onto the photoresist pattern. The overall process window could be adjusted to yield nanogap dimensions from above 100 nm to sub-10 nm as well as for metal layer thicknesses from 20 nm to above 150 nm. The cross section of the metal nanogaps were modeled statistically in order to predict the evaporation process and support near-field enhancement simulations with a realistic geometry. A 3D periodic surface integral approach was used to accurately model electric near and far field intensities. As predicted by the simulations, the plasmon resonance of the Au nanogap array was found to be highly tunable in the visible spectrum by changing of the nanogap dimensions. Both Raman and Fluorescence enhancement measurements were conducted to study the dependency of the plasmon resonance on the signal enhancement. The enhancement of both Raman and Fluorescence was found to scale with the resonance magnitude leading to strongest values for plasmon resonances in between the excitation and detection frequency. Average enhancement factors were determined to exceed 1x106 in the case of SERS on a self assembled monolayer and >50 for the enhancement of the fluorophore Dylight 649. Originating from the dense periodic array and the well controlled pattern geometry, the enhancement was found to be highly reproducibly over the whole sensor area with exceptionally low standard deviations below 3%.

8424-70, Poster Session

Transverse averages of the Gouy phase shift and their relation with the irradiance moments of a beam

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The Gouy phase shift is a well-known axial phase anomaly which is exhibited by any focused disturbance, including light and acoustic waves (see, for example, Refs. 1-4). In practice, this phase shift plays an important role in Optics, ranging from lateral trapping of small particles and highly focused radially polarized beam used in nanooptics, to applications of ultra-short laser pulses. Many efforts have been made to investigate the physical origin of the Gouy phase shift in order to provide an intuitive interpretation of it in terms of analytical properties of the beam.

In the present work, the Gouy phase shift is investigated by means of certain normalized averages at each transverse plane z, namely, its normalized weighted average across the beam profile, and its (normalized) transverse average per unit length. In particular, explicit expressions for these quantities have been found, which involve the well-known second-order irradiance moments describing, in a measurable way, the overall spatial behavior of a field: beam width, far-field divergence and position of the waist plane [5,6].

1. R. W. Boyd, J. Opt. Soc. Am. 70, 877-880 (1980)

2. A. E. Siegman, Lasers, University Science (1986)

3. S. Feng, H. G. Winful, Opt. Lett. 26, 485-487 (2001)

4. H. Chen, Q. Zhan, Y. Zhang, Y-P. Li, Phys. Lett. A 371, 259-261 (2007)

5. P. M. Mejías, R. Martínez-Herrero, G. Piquero, J. Movilla, Prog. Quantum Electron. 26, 65-130 (2002)

6. R. Martínez-Herrero, P. M. Mejías, G. Piquero, Characterization of Partially Polarized Light Fields, Springer (2009)

8424-71, Poster Session

Creation and investigation of self-organized hybrid nanostructures based on bacteriorhodopsin and silver nanoparticles

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Creation of hybrid nanostructures, composed of 3 components: nanoparticle, spacer, functional molecule, as one of ways for expansion of composite materials functionalities is considered. As a functional molecule can be used photochromic, photoluminescent, electroluminescent and other photoactive molecules. The offered technological methods of creation of hybrid nanostructures are based on mechanisms of specific linking and self-organizing.

Bacteriorhodopsin (BR) is a photosensitive membrane protein from Halobacterium salinarum. BR - the unique biomolecular structure capable for many years to keep the photoelectric and photochromic properties. In the ground state bacteriorhodopsin absorbs on wavelength 570 nm (basic state BR570). After the light quantum absorption, BR molecule passes through the sequence of states (intermediates) and spontaneously returns to the ground state. A key intermediate of BR photocycle is thermorelaxing state M412. The challenge of BR photochemistry is to control of photocycle and lifetimes of their basic intermediates.

Features of synthesis and properties of hybrid nanostructures based on BR and silver nanoparticles with polylysine as spacers are presented in this work. Optimum concentrations of components and conditions of synthesis of hybrid nanostructures are shown. Influence of modificating inorganic compounds (such as $Na_2B_4O_7$, K_2CO_3, lysine and other) in correlation of pH change on spectral characteristics of hybrid nanostructure components. For the first time intermediate M412 is stabilized as the ground state of BR with saving of photochromic properties of BR in suspension of hybrid nanostructures.

The developed technological methods can find application in photonics, optics, optoelectronics and in improvement nanobiotechnological detecting methods of biological molecules.

8424-72, Poster Session

Integration of nanoscale features into high efficiency III-nitride light-emitting diodes

S. Kim, Korea Photonics Technology Institute (Korea, Republic of)

Nanopatterned aluminum nitride (NP-AlN) templates were used to enhance the light extraction efficiency of the light-emitting diodes (LEDs). Here, the NP-AlN interlayer between the sapphire substrate and GaN-based LED was used as an effective light outcoupling layer at the direction of bottom side and as a buffer layer for growth of GaN LEDs. The cross-sectional transmission electron microscopy (TEM) analysis showed that the formation of stacking faults and voids could help reduce the threading dislocations. Micro Raman spectra also revealed that the GaN-based epilayer grown on the NP-AlN template had smaller residual stress than that grown on a planar sapphire substrate. The normalized electroluminescence (EL) spectra at the top and bottom sides of device revealed that the enhancement of the bottom side emission of the LED with the NP-AlN interlayer was more notable than a planar sapphire substrate due to the graded-refractive-index (GRIN) effect of the NP-AlN.

8424-73, Poster Session

Nanoparticles size control at ultrashort laser ablation of gold thin film

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In this work we present results on nanoparticles fabrication at ultrashort laser ablation of gold thin film. The influence of temperature depth profile on the decomposition features of the material is studied on the basis theoretical model incorporated molecular dynamics simulation and two-temperature diffusion model. The results indicate that the characteristics of nanoparticles produced at ablation of thin film are different compared to the case of bulk material ablation. Due to the homogenous heating in depth of the film, its ablation is realized via decomposition into gas phase and nanoparticles with narrower size distribution compared to the case of bulk material. Furthermore, the limitation of the heated volume in thin film geometry results in clearly expressed dependence of the applied laser fluence on the width of the nanoparticle size distribution. The laser fluence is found to be an efficient parameter for controlling the properties of produced nanoparticles. Experiments on plume composition at ultrashort laser ablation of thin gold film and bulk target are also performed. The experimental results confirm the theoretically predicted narrowing of the particle size distribution at laser ablation of thin film.

8424-74, Poster Session

On the propagating and evanescent waves associated to azimuthally polarized non-paraxial fields

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Highly focused light is currently considered in a large number of important applications in nanooptics [1]. Among the different vectorial formulations of non-paraxial electromagnetic fields reported in the literature, we investigate the representation based on the plane-wave angular spectrum (see, for example, [2-5]). Such kind of decomposition allows one to separate the contribution of the propagating and evanescent waves. Both types of waves can be written, in turn, as the sum of two terms: one of them is transverse to the propagation direction; another one exhibits a nonzero longitudinal component [6].

In the present work, analytical expressions are given for the spatial shape of the above propagating and evanescent parts of the light field, and a comparison has been established between the relative weight of their respective transverse and longitudinal components.

Attention is focused on azimuthally polarized non-paraxial fields. The special case of fields that remain azimuthally polarized upon free propagation is also studied. The results are applied to several examples of interest.

References

1. I. Novotny, B. Hecht, Principles of Nano-Optics, Cambridge University Press, Cambridge (2007)

2. P. C. Chaumet, J. Opt. Soc. Am. A 23, 3197 (2006)

3. H. M. Guo, J. B. Chen, S. L. Zhuang, Opt. Express 14, 2095 (2006)

4. R. Martínez-Herrero, P. M. Mejías, Opt. Express 16, 9021 (2008)

5. R. Martínez-Herrero, P. M. Mejías, G. Piquero, Characterization of Partially Polarized Light Fields, Springer, Berlin (2009)

6. R. Martínez-Herrero, P. M. Mejías, I. Juvells, A. Carnicer, Appl. Phys. B: Laser and Optics, DOI 10.1007/s00340-011-4720-z (2011)

8424-75, Poster Session

Unexplained high sensitivity of the reflectance of porous natural photonic structures to the presence of gases and vapours in the atmosphere

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Structurally coloured natural photonic crystals (found in butterflies, beetles and other insects) are made of ordered porous chitin structures. In such photonic crystals, colour changes can be induced by relative gas/vapour concentration variations in a mixed atmosphere. For instance, when the composition of the atmosphere changes, the colour of Morpho sulkowskyi butterfly is modified [1]. Based on this effect, Potyrailo and coworkers demonstrated experimentally the possibility to identify closely related vapours (water, methanol, ethanol, isomers of dichloroethylene) [1]. They explained their observations by the occurrence of different spatial periodicities in the nanostructures from different regions of the butterfly wing: different photonic crystal periods are thought to be responsible for the wavelength selective optical response [1]. Recently, Biró and coworkers investigated four butterfly species and demonstrated fast, reproducible species-dependent selective sensitivity to seven test vapours [2].

In spite of increasing interests for such sensors, the fundamental mechanisms at the origin of the selective optical response are still not well understood.

The point is that refractive index variations resulting from the introduction of a specific gas species in the atmosphere are too small to justify entirely the dramatic changes observed in the optical response. Here, we demonstrate through numerical simulations that indeed gas/vapour-induced refractive index changes (typically $\Delta n \approx$ 10^-6 - 10^-7 between dry air and 50% relative humidity water vapour) are too small to produce a significant modification of the spectral reflectance in a representative 3D periodic model of natural porous nanostructures. For this purpose, we used a rigorous coupled wave analysis method for modelling light scattering from inhomogeneous optical media. The origin of the reported colour changes has therefore to be found in chemical modifications of the porous material and their impact on the photonic response.

[1] R. A. Potyrailo et al., Nature Photonics, 2007.

[2] L. Biró et al., Proceedings of SPIE, 2008.

8424-76, Poster Session

Unidirectional surface plasmon polariton excitation at asymmetrical periodic metallodielectric multilayers

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A new configuration of a one-dimensional reflective asymmetrical metallodielectric grating structure for unidirectional excitation of surface plasmon polaritons (SPP) under normal incidence is proposed [1]. The structure is embedded between two different dielectric media and composed of two 1D gratings, each consisting of periodically placed rectangular metal stripes. It is shown that even a small horizontal shift between these two layers, or a change in dielectric contrast of the grating fillings, may redirect energy in the near field. An explanation of unidirectional SPP propagation is given.

SPP can be excited either with a plane wave or with a finite-diameter beam with arbitrary distribution of amplitude and phase (Gaussian, Hermite-Gaussian or Laguerre-Gaussian beams) [2]. Distribution of electromagnetic fields, norm and direction of Poynting vector near the asymmetric gratings in the central area and also near the beam edges is presented for both wide and narrow beams and also a comparison with plane wave excitation is made. Using 3D Gaussian beams enables to visualize the finite SPP propagation length and efficiency of directing effect of the structure. Some of the resonances supported by the two-layered metallodielectric grating structure are presented.

This evident directivity phenomenon exists together with a high concentration of the electromagnetic field at the periodic structure which enables visualization of nanoobjects with resolution better than specified by Rayleigh criterion. The configurations analyzed may be useful in designing optical devices as optical switches, elements of VLSI devices, light harvesting structures for photodetectors or, in general, in any case where efficient control of energy propagation directivity is of primary importance.

References:

[1] A. Roszkiewicz, W. Nasalski, J. Phys. B: At. Mol. Opt. Phys., 43 (2010) 185401

[2] W. Nasalski, Phys. Rev. E, 74 (2006) 056613

8424-77, Poster Session

Highly efficient Förster resonance energy transfer in hybrid organic/inorganic semiconductor nanostructures

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Highly luminescent semiconductor nanocrystals or quantum dots (QDs) possess a number of interesting and important properties that are tunable thanks to their size-dependent discrete electronic spectra. In this work we studied the optical properties of a novel type of hybrid structures that combine CdTe QDs with organic dye molecules (Pseudocyanine iodide) in a J-aggregate state. Due to the excitonic nature of electronic excitations, J-aggregates have the narrowest absorption and luminescence bands among organic materials, large oscillator strengths and giant third-order nonlinear susceptibility. In developed structures optical energy harvested by the quantum dots as artificial antennas then transferred to J-aggregates to enhance the photostability and efficiency of the carriers recombination. To fabricate CdTe/J-aggregates hybrid nanostructures we have used an approach based on electrostatic interaction between the positively charged dye and CdTe QDs capped with thioglycolic acid and, thus, carrying a negative charge. In order to develop an efficient hybrid material operating in the FRET regime, we carefully selected the PL colors (diameters) of the QD to be optically coupled with absorption of J-aggregates. We took advantage of extremely thin ligand shell (~0.5 nm) of CdTe QDs, which insures high efficiency of energy transfer. Formed QD/J-aggregate FRET system shows the broadband absorption in the visible and the ultraviolet part of the spectrum typical of QDs, along with the narrow emission linewidths characteristic of J-band emitters (~15 nm full width at half-maximum). We use absorption and photoluminescence spectroscopy and photoluminescence lifetime studies to conclude that efficiency of energy transfer is 95%.

Also we report on development of active whispering-gallery microcavities integrated with with hybrid QDs/J-aggregate shell. Results of micro-PL spectroscopy and PL lifetime imaging confirm strong quenching of QDs emission and multifold shortening of their photoluminescence lifetime, which is consistent with highly efficient FRET in hybrid organic/inorganic semiconductor nanostructures coupled to microcavity modes.

8424-78, Poster Session

Enhanced photoluminescence of Alq3 via patterned array silver dendritic nanostructures

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We demonstrate a well-controlled silver morphology with various nanostructure, such as semi-ball, jungle, and dendritic, by an electrical deposition process. The morphology of silver can be exactly controlled via different reaction time and solvent concentration. We find the formation of the silver nanostructure follows the diffusion limited aggregation model. An array pattern of silver nanostructure was fabricated when the fabricating process of the silver nanostructure was applied on a conductive substrate (ITO) under a modified electrical filed. The absorption spectra of these silver nanostructures fabricated for different reaction times (t=5 sec, 10 sec, 20sec) were measured using a UV-VIS spectroscopy. A broad-band absorption feature with a narrow resonance peak can be clearly seen in the spectrum. The resonance peak shifts to a longer wavelength when the silver morphology is changed from semi-ball to the dendritic nanostructure. The resonance peak shifts are due to inter-nanowire plasmon coupling, resulting from decreased inter-nanowire distance when reaction time of electrochemical process.

A thickness 200 nm of Alq3 thin-film was deposited on the array-patterned substrate with various silver nanostructures by a high vacuum thermal coater. The photoluminescence of the fabricated sample was measured using a cw. He-Cd laser and a monochromator. Photoluminescence spectra reveal the peak of emission locates at 504 nm. The intensity of emission peak depends on the silver morphology. We explore this remarkable enhancement of the emission rates and intensities resulting from the efficient energy transfer from electron-hole pair recombination in the QW to vibrations of SPs at metal-coated surface of the Alg3 heterostructure. This organic semiconductor SP coupling is expected to lead to a new class of super bright LEDS that offer realistic alternative to conventional fluorescent. The result can help us to open the application of the silver patterned-array with dendritic nanostructure in advanced nanoelectronic device.

8424-79, Poster Session

Fabrication of large-area bi-layer wire-grid polarizers for display technology using EUV interference lithography

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Metallic wire-grid polarizers transmit TM-polarized light (transverse magnetic) and reflect TE polarization (transverse electric) efficiently. They have been already used in radio, microwave, and IR spectral regions [1]. Wire-grid polarizers are compact and planar and show high performance over a wide incident angle and wavelength range. They are also compatible with integrated circuit (IC) fabrication, which simplifies their use as optical components in nanophotonic, fiber optic, display, and detector devices. Single layer metal wire-grid polarizers mostly involve lift-off or reactive ion etching processes [2], which significantly increase their production costs.

In this work, we present bi-layer wire-grid polarizers [3] with sub-100 nm periodicity, which can be obtained by evaporating a metal film onto a photoresist (PR) grating, leading to two metal gratings separated by a certain distance and laterally shifted by a half period. The fabrication process involves only PR patterning and metal evaporation, which is much simple and cost effective. We first studied the optical response of the Al bi-layer wire-grid polarizers with various periodicities, duty cycle, metal layer thickness, as well as the separation distance between two metal gratings using finite element method. We found better polarization performance of an optimized bi-layer wire-grid polarizer compared to single-layer one. Considering the feasible nano-fabrication parameters, large-area bi-layer polarizers with period of 80 nm and metal layer thickness of 30 nm were fabricated using our newly developed scanning exposure strategy with EUV interference lithography. Optical measurements showed transmission up to 80% and extinction of 30 dB (103) and broadband polarizing behavior down to 280 nm, in accordance with our simulations and design. These results demonstrate that Al bi-layer wire-grid polarizers can be used as low-cost, high-performance, and broadband polarizers. In future, bilayer wire-grids may find many applications with their high performance, low-cost manufacturability, and IC technology-compatible fabrication.

[1] S. W. Ahn et al., “Fabrication of a 50 nm half-pitch wire grid polarizer using nanoimprint lithography,” Nanotechnology, 16, 1874 (2005).

[2] J. J. Wang, et. al., "High-performance nanowire-grid polarizers," Opt. Lett., 30, 195 (2005).

[3] Y. Ekinci et. al., "Bilayer Al wire-grids as broadband and high-performance polarizers," Opt. Express 14, 2323 (2006).

8424-80, Poster Session

Colloidal QDs-polymer nanocomposites

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Nanometer-size colloidal semiconductor nanocrystals, or Quantum Dots (QD), are very prospective active centers because their light emission is highly efficient and temperature-independent. Furthermore, the emission wavelength can be easily tuned by controlling the QD chemical nature and size [1]. Nanocomposites based on the incorporation of QDs inside a polymer matrix are very promising materials for application in future photonic devices because they combine the properties of QDs with the technologies of polymers (thin film processing, UV and e-beam lithographic properties) [2]. In the present work some basic applications of these new materials have been studied. Firstly, the fabrication of planar and linear waveguides based on the incorporation of CdS, CdSe and CdTe in PMMA and SU-8 are demonstrated. As a result, photoluminescence (PL) of the QDs are coupled to a waveguide mode, being it able to obtain multicolor waveguiding. Secondly, nanocomposite films have been evaluated as down-shift wavelength converters to improve the efficiency of solar cells [3]. The idea is to use the QDs to absorb most of the UV radiation, which is not producing high quantum efficiency in silicon solar cells, and convert into visible light by means of its PL. These results can be the basis for new active integrated optical devices.

[1] N. Tomczak, D. Janczeuski,, M. Han, G. Julius Vancso, "Designer polymer quantum dots architectures", Progress in Polymer Science, 34, 393-340, 2009.

[2] I Suárez, H Gordillo, R Abargues, S Albert and J Mart´ınez-Pastor, "Photoluminescence waveguiding in CdSe and CdTe QDs-PMMA nanocomposite films", Nanotechnology, 22, 2011.

[3] L.H. Slooff, R. Kinderman, A.R. Burgersm N.J. Bakker, J.A.M. van Roosmalen, A. Büchtemann, R. Dans, M. Schleusener, "Efficienct enhancenement of solar cells by application af a polymer coating containing a luminiscent dye", Transactions of the ASME, 129, 272-276, 2007.

8424-81, Poster Session

Surface plasmons in the near UV wavelength range in circular thin metal film gratings

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Nowadays surface plasmons (SPs) - collective electron oscillations existing at the interface of a metal-dielectric that let one to squeeze and guide light energy in the sub wavelength distances - are in focus of scientific research due to its enormously wide application spectrum in future integrated analytical devices, biological specimen sensing, trapping, etc [1].

We present the study of surface plasmons excitation, propagation in the near UV region (405 nm, 365 nm, and 193 nm) in circular thin metal film diaphragms compound of the concentric sub wavelength nanoslit grooves. The role of Wood anomalies and Fabry-Perot cavity resonances is investigated as well. Mutual connection and influence between the mentioned phenomena is analyzed in order to reveal the electric field behavior after interaction with the circular grating samples in the near field area. For this purpose we utilize the models of an ideal metal-insulator-metal (MIM) waveguide, a 1D grating followed by a 3D grating configuration involving Nelder-Mead minimization routine, Fourier modal method (FMM) and Finite-difference time-domain method (FDTD) [2]. Every subsequent model is supposed to contain the previous and initially is used to confirm its results. The circular thin metal film diaphragms made of several materials and of different geometries are examined. The possibility to control characteristics (amplitude, phase, polarization) of the transmitted electric field components by means of the optimum combination of the thin metal film grating features (grating thickness, period and pitch of grooves) and incident light parameters (polarization, phase) is shown.

[1] J.A. Schuller, E.S. Barnard, W. Cai, Y.C. Jun, J.S. White, M.L. Brongersma, Nature Mater. 9, 193 2010

[2] P. Lalanne, M. Besbes, J.P. Hugonin, S. van Haver, O.T.A. Janssen, A.M. Nugrowati, M. Xu, S.F. Pereira, H.P. Urbach, A.S. van de Nes, P. Bienstman, G. Granet, A. Moreau, S. Helfert, M. Sukharev, T. Seideman, F. Baida, B. Guizal, D. van Labeke, JEOS: RP, 2, 07022, 2007

8424-82, Poster Session

Integrated silicon contradirectional couplers: modeling and experiment

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Wavelength-division multiplexing (WDM) networks are a promising solution for high-speed silicon optical interconnects. Silicon contradirectional couplers [1, 2] have great potential as reconfigurable add-drop optical multiplexers (ROADMs) for WDM applications. They have the advantages of flat-peak responses, broadband operation, and easy integration. We have recently demonstrated silicon contradirectional couplers in silicon rib waveguides with high reflectivities, low insertion losses, and controlled bandwidths in a range of 0.35 to 1.38 nm [1]. By engineering the coupler structure, including the perturbations, their spectral responses can be easily tailored to specific applications. Here we present numerical modeling of silicon contradirectional couplers in both sidewall-modulated strip waveguides and slab-modulated rib waveguides, with the fabrication effects taken into consideration. The designed devices were fabricated using a CMOS-compatible silicon-on-insulator (SOI) technology at Imec, Belgium accessed via ePIXfab.

The distributed coupling coefficients of the contradirectional couplers are calculated based on coupled-mode theory, with the effective indices and mode profiles calculated using a numerical mode solver. Since the design of the contradirectional couplers requires sub-wavelength features (tens to hundreds of nanometers) for the dielectric perturbations, accounting for fabrication-caused deviations is critical for accurate modeling. The approximation effects introduced during the processes of optical lithography and plasma-etch are included in the model that shows good agreement with the measurements. The transfer-matrix method is used to calculate the power coupling efficiency of the contradirectional coupler, which allows thorough optimization and engineering of the spectral response. Using this method, we compare responses of the contradirectional couplers with various apodizations to suppress their sidelopes. The integration of these contradirectional couplers with other photonic devices, e.g., microring resonators, is also discussed.

References

[1] D. T. H. Tan, K. Ikeda, S. Zamek, A. Mizrahi, M. P. Nezhad, A. V. Krishnamoorthy, K. Raj, J. E. Cunningham, X. Zheng, I. Shubin, Y. Luo, and Y. Fainman, Opt. Express, "Wide bandwidth, low loss 1 by 4 wavelength division multiplexer on silicon for optical interconnects", vol. 19, pp. 2401-2409, 2011.

[2] W. Shi, X. Wang, W. Zhang, L. Chrostowski, and N. A. F. Jaeger, "Contradirectional couplers in silicon-on-insulator rib waveguides", Opt. Lett., vol. 36, pp. 3999-4001, 2011.

8424-83, Poster Session

Ultrafast plasmonic photoemission and electron acceleration from metallic nanostructures

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It was recently demonstrated that various ultrafast, strong-field processes can take place in the field of propagating surface plasmons including tunneling photoemission at low laser intensities, keV electron acceleration and so on. This time, we investigated ultrafast plasmonic photoemission and electron acceleration from various metallic nanoparticles by illuminating them with ultrashort laser pulses with 70-fs duration. We lithographically fabricated a dense array of gold nanoparticles resonant and off-resonant with respect to the spectrum of the broadband femtosecond laser. Photoemitted electrons were captured by a time-of-flight electron spectrometer. As opposed to propagating surface plasmons, the field of localized plasmons can exhibit higher field enhancement, on the other hand, a shorter field decay length is expected. Accordingly, we observed lower electron kinetic energies, compared to previous measurements with propagating surface plasmons. It was also observed that the resulting electron energy spetrum is highly sensitive to the actual field distribution in the vicinity of the nanorod-type and bowtie-type structures. The measured spectra can be well reproduced by a semiclassical model of the plasmonic photoemission/acceleration process. In the simulations we include a realistic description of the nanoparticle geometry based on the boundary element method which enables us to trace the underlying physical processes with high precision. The observed phenomena can have important applications in the generation and all-optical acceleration of femtosecond electron bunches for ultrafast time-resolved methods as well as in understanding the mechanisms of THz generation from nanostructured surfaces.

8424-84, Poster Session

Controlling the emission features of two-chromophore nano-sources with coaxial nanowires

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Hybrid organic-inorganic nano-sources are attractive building blocks for nanoscale photonic devices. The mixing of two or three emitters can be used for tuning the photoluminescence (PL) features, such as the color and the decay time. But complex charge and energy transfers make problematical the prediction of the PL behavior.

We show how hybrid nanowires (NWs) with a coaxial arrangement of the two emitters can result in the fine tuning of the PL features at the nanometer scale. In this purpose, PPV (green emission) and [Mo6Br8F6]2- clusters (red to near IR) were selected because they exhibit distinct spectral PL emission as well as no overlapping between their absorption and emission spectral range. The 1 nm-size [Mo6Br8F6] TBA clusters were dispersed in an insulating PMMA matrix to spatially separate the two chromophors. Coaxial NWs with [PMMA-(Mo6Br8F6)2-] as a core and PPV as a shell were prepared by a template strategy. The PL study shows that the resulting spectra can be simply decomposed by the sum of the spectrum of each chromophor balanced by the relative proportion of each material. It thus confirms the neglictible coupling between the two chromophors. As a result, it is possible to anticipate, i.e. to control on the CIE x-y diagram, the color of the light emitted by the NWs. The PL color is anticipated by an interpolation of the x-y coordinates for each chromophor with a remarkable nanoscale resolution. Moreover, a time-resolved PL study reveals the superposition of the fluorescent and phosphorescent nature of PPV and clusters, respectively. Their potential use as one-dimensional nanophotonic emitters will be discussed.

Garreau A., Cordier S., Molard Y., Massuyeau F., Bulou A., Wéry J.,Faulques E., Duvail J.L.; article in preparation

8424-85, Poster Session

Separation of different shape gold nanostructures from a wet chemistry route and stability study upon irradiation with femtosecond laser

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Reduction of a material's size to the nanometric length scale (which is the length scale of the electron motion that determines the material properties) makes it sensitive to further changes in size or shape. We synthesized a mixture composed of different gold nanoparticles using the wet chemistry method described in [1], except that the AgNO3 solution was not added into the growth solution. The final solution contained a mixture of long nanorods, balls, disks and different spherical .To separate appropriate shape nanoparticles from the reaction mixture, the solution was precipitated in hot CTAB solution and then centrifuged [2]. The stability of the nanoparticles upon irradiation with femtosecond laser has been studied. When the electron gas of noble nanoparticles is excited by a femtosecond laser pulse bleaching of the plasmon absorption occurs and the energy is well redistributed on the surface by the electron-electron interaction. Simultaneously there exists thermally equilibration of the electron gas with the lattice by electron-phonon scattering, then the energy is released to the surrounding solvent by photon-photon interaction [3]. One of the mechanisms of the shape transition is due to the multiphoton ionization processes, the charge repulsion on the surface leading to melting since transformation into a sphere minimizes the electrostatic repulsion between the charges in the ionized nanoparticles [4]. Lately, we have presented the investigations of optical properties of nanorods under fs laser illumination [5]. Acordingly, in this work we have observed the preferential changes in shapes of metal nanoparticles into spheres.

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References

1. T. K. Sau and C. J. Murphy, Langmuir, 2004, 20, 6414-6420.

2. K. Park, H. Koerner and R. A. Vaia, Nano Letters, 10, 1433-1439.

3. S. Link, C. Burda, B. Nikoobakht and M. A. El-Sayed, Chemical Physics Letters, 1999, 315, 12-18.

4. S. Link, C. Burda, M. B. Mohamed, B. Nikoobakht and M. A. El-Sayed, Journal of Physical Chemistry A, 1999, 103, X1-1170.

5. J. Olesiak-Banska, et al. (2011) submitted.

8424-86, Poster Session

The bamboo-like nanotubes as nanomaterial for energy conversion

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Among the large variety of the modern materials of nano- and bioelectronics the carbon nanostructures of the complex form are one of the most perspective materials. In particular, the field-emission cathodes on a basis of these structures can be used in the medical radiography.

Also the carbon nanostructure of the complex form can be applied at the design of the medical electronic equipment. For example, they can be used in a work of the field emission display. The results of the theoretical and experimental investigations of the emission properties of the bamboo-like nanotubes are presented in this paper.

The original synthesis technique of the bamboo-like nanostructures is proposed in this work. The carbon bamboo-like nanotubes were synthesized using the etching of the nanotubes sample by the high-frequency oxygen plasma during the 30, 60 sec. Such synthesis technology provides the high efficiency of the bamboo-like nanotubes growth. Experimentally the field emission properties of the bamboo-like nanostructure were studied using the current-voltage characteristics of the films measured before and after oxygen plasma treatment. It is established that the emission properties of the carbon nanotube films after oxygen plasma treatment are higher in compare to those of the untreated films.

Theoretical investigation of the field emission properties of the bamboo-like nanotubes is carried out by the quantum-chemical tight-binding method. By means of this method we have determined influence the number of bridges on the emission properties of the bamboo-like nanotubes. It was revealed that the bamboo-like nanotube (10, 10) with two bridges has a lowest ionization potential.

Thus one can conclude that the carbon bamboo-like nanotubes can be applied as nanoemitters with high field emission properties. Films with similar structures can be used as cathodes ensuring a stable current under small voltage in nano- and mictroelectronic devices.

8424-87, Poster Session

Surface structure enhanced second harmonic generation in organic nanofibers

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Electron beam lithography-defined regular arrays of gold nanostructures with various shapes, squares or triangles, induce significant local field enhancement effects, which are used to modificate the threshold for second harmonic generation in nonlinearlly optically active self-assembled organic nanofibers (CNHP4). Both the nanostructures dimension and arrays pitch distance are choose to maximize field enhancement effects with special attention to the surface plasmon excitation, both localized surface plasmons (LSPs) and surface plasmons polaritons (SPPs). The local field enhancement effects are determined quantitatively using a newly developed laser ablation method, which bases on a thin film coating of the structures with a simple polymer (PMMA). The method utilizes sub 100 femto-second laser pulses (wavelength between 750 and 800 nm) from a custom built laser scanning microscope which induce electrical field enhancements on and around the gold nanostructures. These enhancements lower the ablation threshold and this is reflected in a permanent sub-diffractional surface pattern formation, which is subsequently checked via scanning electron microscopy and atomic force microscopy. By integrating organic nanofibers on the gold nanostructures, using soft transfer technique, it is shown that the threshold for second harmonic generation is significantly modified by the tailored local field enhancements. The method is used to quantify the near-field coupling between the structured substrate and the nanofibers.

8424-88, Poster Session

Laser cooling with Tm3+: doped nano-crystals of oxy-fluoride glass ceramic

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We present a new scheme for laser cooling with the Tm3+ - doped oxy-fluoride glass ceramic (GC) samples. The physical mechanism of radiation cooling of solids by anti-Stokes fluorescence was originally proposed in 1929 [1] and experimentally observed for the first time by Epstein's research team in ytterbium-doped ZBLANP glass in 1995 [2]. Some specific combinations of the rare-earth ions, low phonon energy host materials, and the wavelength of the incident radiation can provide anti-Stokes interaction resulting in phonon absorption accompanied by the cooling of the host material. At the present time laser cooling of solids has been demonstrated in a number of Yb3+, Tm3+, and Er3+ doped low phonon energy glass and crystal hosts, which provide high quantum efficiency but can have limited mechanical and chemical stability.

We propose a new approach to laser cooling of solids with anti-Stokes fluorescence based on the Tm3+ - doped GC samples. These GC samples have a composite structure with fluoride nano-crystals sized 7-19 nm doped with Tm3+ ions, distributed homogenously in the oxide glass matrix. It is shown that such GC samples with high chemical and mechanical stability related to oxide glass and low phonon energy of the fluoride nano-crystals, which trap a majority of Tm3+ ions participating in the cooling process, are particularly suitable for laser cooling of solids. A low phonon energy local environment of Tm3+ ions in the fluoride nano-crystals provides high quantum efficiency, which is a crucial condition for laser cooling of solids. At the same time, the high chemical and mechanical stability of the oxide glass make the Tm3+ - doped oxy-fluoride GC useful for many applications. Without loss of generality laser cooling with another rare-earth ions doped in oxy-fluoride GC can also be realized.

[1]. P. Pringsheim, Z. Phys. 57, 739 (1929).

[2]. R.I. Epstein, M.I. Buchwald, B.C. Edwards, T.R. Gosnell, C.E. Mungan, Nature (London) 377, 500-502 (1995).

8424-89, Poster Session

Strong magnetic resonance of coupled aluminum nanodisks on top of a silicon waveguide

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We study the electromagnetic behavior of a structure consisting of coupled aluminum (Al) nanodisks on a silicon waveguide at telecom wavelengths. Numerical simulations (performed with CST Microwave Studio) show that the fundamental TE waveguide mode excites a localized magnetic plasmon resonance between adjacent nanodisks with suitable dimensions, leading to transmission dips. For a sufficient number of disks (periodically distributed along the propagation direction), the structure supports a magnetic mode arising from a magneto-inductive coupling between neighboring nanodisks, as revealed by an Eigenmode analysis. The influence of the number and dimensions of the disks is also analyzed.

To verify the theoretical predictions, we follow a two-step method to fabricate several samples of the proposed structure with different number of disks (thickness of 20 nm and diameter of 170 nm) separated by 30 nm, and placed on a 9 µm long silicon waveguide (450 nm of width and 250 nm of thickness). First, an e-beam lithography process was employed to create the Al nanodisks. After exposing and developing, aluminum was deposited by evaporation followed by a lift-off process. At this stage, alignment marks were included to ensure the right placement of the nanodisks on the photonic waveguides. In a second step, the waveguides were fabricated. A new e-beam lithography process was carried out to expose the waveguides and, as mentioned above, align them with the previously fabricated nanodisks. After developing, the waveguide etching was realized by means of a RIE (Reactive Ion Etching) process carried out by using an ICP (Inductively Coupled Plasma) tool.

The transmission response of the samples was measured for both polarizations through an end-fire set-up, confirming that the strong resonances are only present for TE polarization. Measurements and simulations are in good agreement, showing that the resonances strength is maximized for three coupled nanodisks.

8424-90, Poster Session

CW z-scan measurements using Fresnel diffraction theory in TiO2 nanocrystals prepared by pulsed laser ablation in water

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The colloidal solution of TiO2 Nanoparticles was achieved by pulsed laser ablation. A titanium plate was immersed in 2ml distilled water and ablated by a Nd:YAG laser (1064nm) with 240ns pulse duration, 2kHz repetition rate and 0.4 mJ pulse energy. The optimum irradiation time was 1 hour, because by exceeding this time the thick colloidal solution would scatter the laser beam and disturb the ablation process. Optical absorption spectrum was obtained using a Perkin Elmer Lambda25 model spectrometer with a resolution of 1nm in a wavelength ranging from 200 to 900nm. It shows a peak about 314 nm. The band gap energy of the NPs was measured with the help of their optical absorption spectrum. It was about 3.3 eV. Moreover an EM 208 S Philips model transmission electron microscope operating at an accelerating voltage of 100kV was employed to perform electron microscopy analysis. The corresponding selected area electron diffraction (SAED) patterns reveal the crystalline structures of the NPs. The average size is 11nm and maximum size distribution is at 5-10 nm. The optical refractive nonlinearity was measured by closed-aperture z-scan technique. A CW He-Ne laser at 632.8nm at 50mW was employed to study nonlinear properties. The closed-aperture z-scan experiment was carried out using Fresnel diffraction theory. The beam was focused by a lens. We put the sample nearby the focus. The diffraction rings pattern was observed in the far field. Using the calculated nonlinear refraction index from the closed-aperture z-scan, the phase shift at the sample position was obtained. Then, the theoretical intensity pattern in the far field was plotted. It was in good agreement with the experimental one.

8424-91, Poster Session

Control of spontaneous emission in semi-conducting photonic nanowires

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Photonic nanowires (PWs) are simple dielectric structures for which a very efficient and broadband spontaneous emission (SE) control has been predicted [1]. Recently, a single photon source featuring a record high efficiency was demonstrated using this geometry [2]. Using time-resolved micro-photoluminescence, we investigate directly the SE of single InAs quantum dots (QDs) embedded in GaAs PWs and demonstrate performances that fully confirm the theoretical predictions [3]. In addition, we discuss recent results obtained on elliptical wires that ensure an efficient control of the photon polarization [4].

We first consider cylindrical PWs, defined within a top-down fabrication process. For diameters leading to the optimal confinement of the fundamental guided mode HE11 (d/lambda~0.25, lambda~950nm), the coupling to HE11 (2-time polarization degenerated) dominates the SE process and a maximum enhancement of the SE rate by a factor of 1.5 is reached . When the diameter is decreased by 100nm, the guided mode is completely deconfined. The coupling to this mode vanishes, thus allowing the coupling to the other radiation modes to be probed [3]. In these conditions, a SE inhibition factor of 16, equivalent to the one obtained in state-of-the-art 2D photonic crystals, is measured.

Moreover, a PW featuring an elliptical section provides a very efficient control over the polarization of the emitted photon. In that case, only one guided mode, with a linear polarization oriented along the major axis, is confined in the semiconductor. Polarization-resolved experiments show that the coupling to this single mode can exceed 95% for optimum structures [4]. These results confirm the high potential of PWs for the realization of efficient sources of quantum light.

References

[1] I. Friedler et al. Opt. Express, 17, 2095 (2009).

[2] J. Claudon et al. Nature Photonics. 4, 174 (2010).

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

[4] M. Munsch et al., submitted to PRL (2011).

8424-92, Poster Session

Wavelength dependent third-order nonlinear optical properties of colloidal gold nanorods

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Gold nanorods (NRs) have gained great interest due to their anisotropic shape, which introduces two modes of surface plasmon resonance (SPR) oscillations. The longitudinal and transverse SPR bands result in strong light polarization and frequency dependence, and very large field enhancements [1]. In comparison to nanospheres and nanoshells, NRs provide better tunability of SPR bands in a wider range of optical frequencies, keeping the small size of the nanoparticles. Thus, NRs are finding important applications in linear and nonlinear optical microscopy and medical therapies [2]. In order to design NRs for specific applications, their behaviour under the illumination of light beams of various characteristics need to be known. Quantitative description of light-NRs interactions in a wide range of wavelengths is required.

This contribution reports on the investigations of nonlinear optical properties NRs of the aspect ratio 3.2 and the longitudinal SPR at 850nm [3]. The NRs were synthesized in the seed-grow procedure and additionally stabilized, as was described in [3-4]. Then, the open-aperture and closed aperture Z-scan technique was applied to determine the real and imaginary part of the cubic hyperpolarizability in the range from 550 to 1600nm [5]. The wavelength dependencies of nonlinear refractive index and two-photon absorption cross-section were determined, taking into account the observed saturable absorption effects that were following the dependence described in [6]. The influence of SPR on the nonlinear properties as well as the behaviour of gold NRs in the high intensity fs laser beam are discussed.

[1] Huang, X. et al. Adv Mater 21, 4880 (2009)

[2] Cheng, J. X. et al. Photochem Photobiol 85, 21 (2009)

[3] Olesiak Banska, J. et al. submitted (2011)

[4] a) Sau, T. K. et al. Langmuir 20, 6414 (2004), b) Zweifel, D. A. et al. Chem. Mat. 17, 4256 (2005)

[5] Sheik-Bahae, M. et al. IEEE J Quantum Elect 26, 760 (1990)

[6] Samoc, M. et al. Opt Lett 23, 1295 (1998)

8424-93, Poster Session

Amplification of the evanescent field of free electrons

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We show that the conversion of the evanescent field of free electrons into optical radiation can be enhanced by amplifying the electrons' evanescent field. In the same way a layer of plasmonic metal can be used to amplify evanescent fields in the 'poor-man's supelens', it can be used to enhance Smith-Purcell radiation.

The electromagnetic energy of free electrons exists in the form of

evanescent waves and can be decoupled into light only when they are in close proximity to a slow-wave medium or optical inhomogeneity. Since the exponentially decay rate of such evanescent waves is proportional to the ratio of the frequency of the electromagnetic field to the velocity of the particle, high velocity, relativistic particles are more efficient in generating light in the optical part of the electromagnetic spectrum. Here, instead of increasing the energy of the particles to gain a higher level of conversion, we utilize a thin silver layer to amplify the rapidly decaying evanescent waves of non-relativistic free electrons. A silver layer a few tens of nanometres thick placed between the free electrons and nano-grating provides an order of magnitude enhancement of Smith-Purcell radiation in the UV range.

8424-94, Poster Session

Tunable mid-infrared filter based on the superposition of sub-wavelength gratings

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In 2008, we realized a matrix of 11 filtering devices based on one dimensional sub-wavelength gratings [1]. By varying the grating's period length, slit width or thickness the spectral position

of the transmission resonances can be modified to cover the spectral band of interest. Another approach of multispectral imaging consists in using a tunable filter which means that the spectral position of the transmission resonance can be adjusted using mechanical means. The obtained device allows to detect the spectral signature of various chemical species with increased resolution and accuracy. This contribution deals with design, fabrication and caracterization of a tunable infrared filter in the 3-5 um band based on the superposition of two identical sub-wavelength metallic gratings. By varying the longitudinal space gap G between the two gratings, two behaviours in the transmission spectrum can be observed. If G is bigger than half of the grating period, a Fabry-Perot behaviour allows to perform multispectral imaging with a number of filters than can be adjusted according to needs. By contrast, if G is lower than half of the grating period, the closer the two gratings come, the stronger the coupling is, leading to the appearance of a transmission extinction at large wavelengths. We recently explained the appearance mechanism responsible for this transmission extinction which is of great interest for designing filters with high rejection efficiency [2].

Moreover since the spectral position of this extinction strongly depends on geometrical parameters, we are now able to design a filter with tunable FWHM. The experimental setup consists in a moving grating brought close to a fixed one by a nanometer resolution piezoelectrical device. A visible laser is used to monitor the good parallel positionning of the two diffracting objects. To the best of our knowledge this is the first realization of a tunable dual metallic structure.

References

1. S. Collin, G. Vincent, R. Haïdar, N. Bardou, S. Rommeluère, and J.-L. Pelouard, Phys. Rev. Lett. 104, 027401 (2010).

2. T. Estruch, J. Jaeck, F. Pardo, S. Derelle, J. Primot, J. Pelouard, and R. Haidar, Optics Letters 36, 3160 (2011).

8424-95, Poster Session

A comparison between PECVD and ALD for the fabrication of slot waveguide based sensors

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A slot waveguide consists of one, or more, narrow low refractive index region sandwiched between two regions of higher refractive index. They enable high confinement in the low-index very small region and are very sensitive to either cover medium refractive index change or deposited receptor layer thickness increase [1]. For a full compatibility with CMOS platforms the materials used to make the slot waveguides (core and cladding) have to be deposited at low temperature and only PECVD or ALD techniques can be considered.

By choosing Plasma Enhanced Chemical Vapor Deposited (PECVD) SiC or Atomic Layer Deposited (ALD) TiO2 as cladding, the size of the slot region becomes higher (compare to silicon) due to a weaker optical confinement [2] making their filling for sensing easier. SiC has in this case a superior advantage as it is a stronger material and can easily find applications in harsh environments. ALD layers have the potential to be doped offering the possibility of on chip amplification [3]. By using vertical slot waveguides we increase the tolerance to dimensions deviations during fabrication and do not require the etching of the high refractive index region limiting then scattering losses.

In the paper, we report a 23.9 dB/cm and a 18 dB/cm for the quasi-TM mode in a PECVD Si/SiO2/Si and a ALD TiO2/Al2O3/TiO2 vertical slot waveguide respectively. The roughness of the PECVD layers limit however their use to large slot waveguide while slots as small as 45 nm can be fabricated using ALD making them attractive in cantilever based sensor with improved sensitivity.

References:

[1] F. Dell'Olio and V. M. N. Passaro, "Optical sensing by optimized silicon slot waveguides", Opt. Express, vol. 15, pp. 4977- 4993, 2007.

[2] C.A. Barrios, B. Sanchez, K.B. Gylfason, A. Griol, H. Sohlstrom, M. Holgado, R. Gasquel, "Demonstration of slot-wavegudie strutures on silicon nitride/silicon oxide platform", Opt. Express, vol. 15, pp-6846-6855, 2007

[3] K. Wörhoff, J.D.B. Bradley, F. Ay, D. Geskus, T.P. Blauwendraat, and M. Pollnau, "Reliable low-cost fabrication of low-loss Al2O3:Er3+ waveguides with 5.4-dB optical gain," IEEE J. Quantum Electron., vol. 45, pp. 454-461, 2009

8424-96, Poster Session

Fabrication of ZnO nanostructures and their application in biomedicine

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In the last decade, nanoscale materials have become an area of extensive research due to their potential application in wide areas of science, technology and medicine. In what concerns medicine, inorganic metal oxides have attracted scientific interest as antimicrobial agents because of their safety and stability. Among these, zinc oxide nanoobjects are at the forefront of research due to their unique properties and widespread applications. The advantage of using ZnO nanoparticles is that they exhibit strong pathogenic action to microbes when used in small concentrations. Moreover, these nanoparticles are stable and show great selectivity and heat resistance. Since ZnO nanoparticles possess antibacterial and antifungal activities at low concentrations, then film coatings of such nanoparticles or different kind of nanostructures could be expected to be suitable for preparation of microbe resistant substrates.

In this study, our aim was to synthesize different types of nanostructured ZnO films and investigate their potential application in biomedicine. The properties of ZnO are strongly dependent on the synthesis process and the experimental conditions. Thus, the nanostructures were prepared by pulsed laser deposition (PLD), which allows excellent control over the stoichiometry and surface morphology. The object of interest was HeLa cancer cells grown on the fabricated nanostructures. The influence of the ZnO structure morphology on the HeLa cells viability was studied.

8424-97, Poster Session

Surface enhanced Raman scattering hot spots on single plasmonic Fano-oligomers

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Recently Fano resonances have been extensively investigated in plasmonic oligomers and have shown a promising application in localized surface plasmon resonance (LSPR)-based biosensing. As a result of the strong interparticle coupling, the Fano resonance coincides with strong field enhancements between the particles. This indicates that such a plasmonic oligomer may act as an effective platform to study surface enhanced Raman scattering (SERS) at a single nanostructure level.

Herein, we will present the first SERS investigation of single plasmonic Fano-oligomers. We design and fabricate Au oligomers with a well controlled Fano resonance to examine how the distribution of the SERS enhancement hot spots is affected by the structural geometry and the inhomogeneous adsorption of Raman analytes. Moreover, in the design and analysis, we consider the red-shift of the resonance upon adsorption of the Raman analytes and we calculate the SERS enhancement factor (EF) using |EFex|^2 |EFscat|^2 instead of the more common |EFex|^4 method. In this way, we calculated for the first time the SERS EF maps by correlating their SEM images, experimental dark-field scattering spectra, finite different time domain (FDTD) simulated scattering spectra and Raman spectra. We clearly show that by varying the disk or gap size of the clusters we can turn “on” or “off” of the SERS hot spots at different positions. As a further example, we investigated on a single Au heptamer how the SERS hot spots can be redistributed and the intensity can be strengthened or weakened by the local deposition of a 25 nm carbon nanoparticle (CNP) as the Raman analyte. The excellent agreements between the experimental and calculated SERS hot spot intensities and locations demonstrate the significant importance of the local adsorbing event of the Raman analyte on the SERS hot spots for the design of the favorable SERS substrates. Finally, this method is successfully applied to predict to the relative SERS intensity of a specific Stokes line of the molecules on more complex single plasmonic Fano-oligomers, which is very difficult to judge only based on the optical spectra.

8424-98, Poster Session

Concentration dependence of photo-induced birefringence and second-order susceptibility in all-optical poling

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The optical properties of azobenzene derivatives embedded in a polymer matrix can be manipulated by optical fields. Selective excitation with a polarized optical field leads to photoinduced realignment and consequent birefringence. A combination of fields at a fundamental frequency and its second-harmonic leads to stronger selectivity of excitation, causing photoinduced noncentrosymmetry and hence leading to second-order nonlinear optical response. The latter process is known as all-optical poling. The structure induced during all-optical poling gives rise also to birefringence.

In this paper, we show that the photoinduced birefringence and second-order response show markedly different dependence on the concentration of the photoactive chromophores even when both are simultaneously induced by all-optical poling. The evolution of the photoinduced effects was studied during all-optical poling using polymer samples with varying concentration of Disperse Red 1 embedded in poly(4-vinyl pyridine). The second-order response is diminished at moderate chromophore concentration while birefringence is mitigated only at significantly higher concentration. This result elucidates the importance of chromophore-chromophore intermolecular interactions in the optical properties of the material system. High-dipole-moment chromophores, such as Disperse Red 1, prefer centrosymmetric arrangement for spontaneously formed dimers. It is this additional centrosymmetry that plays against second-order nonlinearity with increasing chromophore concentration. For photoinduced birefringence, however, such interactions are not detrimental as long as the photoinduced realignment is possible, i.e. as long as large chromophore aggregates are not formed.

8424-99, Poster Session

Laser fabrication and optical characterization of large-scale arrays of metal, metal alloys, and semiconductor nanoparticles

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A novel method for high-speed fabrication of large-scale periodic arrays of metal, metal alloys, and semiconductor nanoparticles with diameters of 40 - 200 nm has been developed. The method is based on a combination of lithographic methods with laser-induced transfer of nanodroplets from different material films, resulting in exact spherical particles arranged in arbitrary array geometries. Arrays of nanoparticles consisting of pure metal, metal alloys, and semiconductors have been realized. The size of the particles, their composition, and the geometry and period of the particle array can independently be controlled by lithographic structuring of the material films into small island of material on the substrate. The produced nanoparticle arrays exhibit collective particle resonance modes with diffractive coupling between the individual particles, including their electric and magnetic dipole moments and their electric quadrupole moment, leading to narrow Fano-type resonances. Hexagonal arrays of gold nanoparticles with diameters of 110 nm are demonstrated as effective sensor elements, providing a sensitivity of 365 nm/RIU and a figure of merit of 21.5 in the visible spectral range. For larger metal particles the electric quadrupole moment has to be taken into account. The theoretical approach is based on a solution of the coupled dipole-quadrupole equations, where the dipole and quadrupole polarizabilities of the individual particles are calculated using Mie theory. Extinction and scattering cross sections of the coupled dipole-quadrupole structures are presented and their potential for sensor and metamaterial applications discussed.

8424-100, Poster Session

Dispersion control of propagating surface plasmons on nanoporous gold

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Surface plasmons (SPs) allow short wavelengths and strong confinement of light and form the backbone of current sub-wavelength optics. Their dispersion relation on plane metal/dielectric surfaces follows directly from Maxwell equations and is given as $k_x=(\omega/c)[\varepsilon_m*\varepsilon_d/(\varepsilon_m+\varepsilon_d)]^{0.5}$, where kx describes the wave vector of the surface plasmon and ε_m and ε_d are the dielectric constants of the metal and the dielectric respectively.

To control the dispersion of the surface plasmons, normally ε_d is varied. An increase in ε_d causes a red shift of the surface plasmons at constant kx or an increase of kx for constant surface plasmon frequency ω. However in our experiments we explore the possibility to tune the dispersion of surface plasmons by changing the value of ε_m by introducing a nanoporosity into the metal. In this way a “meta-metal” is created whose effective dielectric constant ε_m governs now the surface plasmon dispersion on its surface.

In order to achieve nanopores with diameters in the range of 10-50nm in gold we dealloyed 12 carat white gold leaf samples. The gold leaf is floated on conc. HNO_3 for different times leading to spongy nanoporous gold films with controlled mean nanopore size. SEM characterization and ellipsometry measurements confirm a porosity of approximately 36.5% .

To map the dispersion relation of the SPs at the nanoporous gold surface, angular resolved reflection measurements were carried out in the Kretchmann configuration (prism coupling). A characteristic dip in reflectivity, which shifted to shorter wavelength with increasing angle of incidence, was identified as the excitation of propagating SPs at the nanoporous gold/air interface. From the angle of reflection and the frequency of the reflection dip the wave vector kx and the frequency ω of the SPs are derived resulting in the experimentally determined dispersion relation. These results were compared with corresponding measurements on solid pure gold leaf and a reference sample of a smooth evaporated solid gold layer. A clear red shift by approximately 0.85 eV of the SP dispersion relation on nanoporous gold is observed resulting in SPs near the infra-red region.

The shift of the dispersion relation towards infra-red wavelengths for nanoporous gold is compared with theoretical calculations in which the εm of the nanoporous gold layer is derived using the Bruggeman effective medium theory. The observed good agreement between experimentally determined and calculated SP dispersion relation confirms, that the Bruggeman effective medium model is suited well to describe the optical properties of the disordered bi-continuous network of gold veins and air pores of the nanoporous gold.

The above set of experiments and analysis proves that the dispersion relation of the SPs can be controlled by the porosity of a metal (independent of the εd of the dielectric). This could allow the tuning of the limiting surface plasmon frequency ωsp into a specific desired spectral range where e.g. the luminescence of the adjacent specific dielectric material should be enhanced or the low group velocity of the SPs around sp should be utilized.

8424-101, Poster Session

Direct lasers-assisted synthesis of localized gold nanoparticles from both Au (III) and Au (I) precursors within a silica monolith

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A solvent-free and laser-assisted growth of gold nanoparticles (Au-NPs) from both Au (III) and Au (I) precursors within a silica monolith is reported. The novelty of the synthetic method lies in that Au-NPs, about 20 nm in diameter and well dispersed in the matrix, were obtained with no need of either reducing and capping agents. Moreover, the described laser-assisted synthetic procedure made it possible to achieve reproducible 2D and 3D patterns of Au-NPs. For this purpose, suitable Au (I) and Au (III) precursors, soluble in dichloromethane , were easily prepared following a well-known procedure.

The mesoporous silica matrix was first loaded with the precursors via a simple impregnation and then irradiated using either a continuous laser = 266 or 532 nm) or a pulsed laser (=800 nm; pulse: 120 fs; repetition rate: 1KHz). The effect of the laser power on the dimensions of the obtained nanoparticles was also investigated.

In all cases, a photothermal gold reduction was observed only in the irradiated area. The reduction of the precursors was followed via Raman and UV-Vis absorption spectroscopies in order to compare the mechanism of Au-NP formation when different lasers and wavelength of irradiation are employed. Moreover, the Au-NP characterization was performed by means of UV-Vis absorption spectroscopy, X-Ray Diffraction and Transmission Electron Microscopy. In all cases the formation of Au-NP was confirmed. When the Au (I) precursor was employed, it was found from X-Ray Diffraction patterns that the nanoparticles were grown with a preferred orientation.

Finally it was proved that the excess of gold precursors can be removed after the Au-NP synthesis by a simple washing of the monolith with a few immersions in the pure solvent.

The stability of the Au-NPs was further tested by a series of heat-treatments up to 500°C, showing that the silica monolith acts as an effective support to prevent the agglomeration of the nanoparticles.
effective support to prevent the agglomeration of the nanoparticles.

8424-102, Poster Session

Blue light-emitting-diodes from poly (N-vinylcarbazole) doped with colloidal quantum dots encapsulated with carbazole terminated ligand: spectroscopic studies and devices

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Blue emitting CdSe/ZnS quantum dots (QDs) were encapsulated with the ligand 11-(N-carbazolyl) undecanoic acid (C11). Steady-state photoluminescence (PL) experiments show an enhancement of the QD emission upon the excitation of the carbazole ligand in solution compared to the situation where a solution with the same concentration of QDs capped with oleic acid (OA) were excited at the same wavelength. This suggests energy transfer from the carbazole moiety to the QD cores. When incorporating the QDs in a poly (N-vinylcarbazole) (PVK) matrix, a significant enhancement of the QD emission upon the excitation of PVK was also observed indicating an efficient energy transfer from PVK to the QDs in the case of C11 capped ligands. Confocal microscopy images of the doped PVK films show clearly better miscibility of PVK and QDs capped with C11 compared with those capped with OA. Nanosecond time-resolved PL experiment shows an evidence of singlet transfer with Förster resonance energy transfer (FRET) efficiency of 39% for the QDs in solution, while 15.6% for the doped PVK film with 30 wt% of the QDs. The smaller efficiency of the singlet energy compared to the overall efficiency of energy transfer suggests an important role for triplet energy transfer.

Electroluminescence devices were prepared with the structure; ITO/PEDOT:PSS/doped PVK with C11 capped QDs/Butyl PBD/Aluminum. Upon applying voltage, the devices show pure blue electroluminescence at low concentration of QDs (5 and 10 wt%) and slightly green blue at higher concentration (30 wt%) with the turn on voltage below 10 V.

8424-103, Poster Session

Photonic properties of two-dimensional photonic crystals based on monolayer of dielectric nanospheres

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The optical properties of two-dimensional (2D) photonic crystal (PhC) slabs based on self-assembled monolayer of dielectric nanospheres are studied. The in-plane transmission spectra of 2D array of dielectric spheres with triangular lattice are investigated using the finite-difference-time-domain (FDTD) method. The structures studied are monolayer of dielectric spheres infiltrated with air ('opals') and air spheres infiltrated with dielectric material ('inverse opals'), with and without glass substrate sustaining the monolayer of spheres. The structures based on monolayer of dielectric nanospheres are considered as PhC slabs as the vertical height of the PhC layer is finite, similar to 2D array of finite height dielectric cylinders. The transmission spectra are calculated for different values of refractive index contrasts between the spheres and the infiltrated material and for different values of filling fractions. In this study, as the refractive index is varied, compact spheres are assumed. As the filling fraction is varied, the refractive index of the dielectric spheres (for opals) and dielectric matrix (for inverse opals), is fixed to be 2.1. For the compact opal structure suspended in air, a narrow photonic band gap

(PBG) is observed in the transmission spectra for the dielectric spheres with refractive index higher than 1.5. The PBG appears for the filling fraction higher than 0.3. While for the opal structure on glass substrate, the PBG is observed for compact dielectric spheres of refractive index higher than 2 and for filling factions higher than 0.48. For the inverse opals suspended in air, the PBG in the transmission spectra is observed for dielectric materials with refractive index higher than 1.5 and when filling fraction is higher than 0.25. The presence of the glass substrate reduces the width of the PBG. However, the PBG can be enlarged when the air spheres are non-compact. The results show that with good choice of refractive indices and filling fractions of realizable dielectric materials we can have PBG in the in-plane direction. The application of the results obtained above is to realize organic PhC microcavity laser. One of the advantages of using nanoparticles is its easy self-assembly fabrication process compared to the costly e-beam lithography process.

8424-104, Poster Session

Hyperspectral near-field imaging for nanophotonics

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The scanning near-field optical microscopy (SNOM) is used to analyze optical phenomena at the sub-wavelength scale such as light localization and propagation in photonic crystals or plasmonic devices. In any case, SNOM experiments rely on the positioning of a local probe in the optical near field of a given structure and on the detection of the surrounding evanescent waves. Depending on the nature of the probe or on the optical detection method, the detected physical properties are the spatial distributions of the amplitude and phase or the intensity of the electric and magnetic components of the probed field.

In this paper, we present the implementation of an innovative hyperspectral near-field imaging method which aims to detect both spectral and spatial properties of an optical nanosystem at the subwavelength scale. The presented method provides a batch of images over a broad spectral range at visible; near-infrared and telecommunication wavelengths. Using this technique, we will report here the near-field observations through the spectrum of the emblematic electromagnetic phenomena involved in photonic crystals and plasmonics such as light waveguiding, trapping or beam shaping.

8424-105, Poster Session

Particle size dependent thermal characterization of gold nanofluid using thermal lens technique

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In this paper we report the usefulness of the photothermal technique, dual beam thermal lens technique, to find the effect of particle size on the thermal diffusivity of the gold nanofluid. Samples with different particle sizes (30 nm to 90 nm) were prepared by citrate reduction of gold chloride in water. As the size of the particle increases plasmon-related absorption peak undergoes very large shifts in wavelength. Thermophysical parameter such as thermal diffusivity is an important characteristic property of any material and accurate values of these parameters are crucial for practical engineering design as well as theoretical modelling, especially in the fields of heat transfer and thermal processing. In the thermal lens technique the sample illuminated using 532 nm radiation from a diode pumped solid state laser. A part of the incident radiation is absorbed by the sample and subsequent nonradiative decay of excited state population results in local heating of the medium. The temperature distribution in the medium mimics the beam profile of the excitation beam and hence a refractive index gradient is created in the medium. Due to this modification in refractive index, the medium mimics a lens, called thermal lens (TL). The thermal lens generally has a negative focal length since most materials expand upon heating and hence have negative temperature coefficient of refractive index. This negative lens causes beam divergence and the signal is detected as a time dependent decrease in power at the center of the beam at far field. The present study shows that the variation of diffusivity of the nanofluid with particle size clearly establishes the fact that thermal properties of nanofluid can be tuned by variation in the particle size.

8424-106, Poster Session

Evolution of plasmonic resonance of gold nano-blocks embedded in dielectric multilayers

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This work presents the theoretical study of metallic nanostructures embedded in dielectric multilayers. Gold nano-blocks are deposited on a dielectric substrate (n1) and covered by a dielectric slab (n2) of thickness d. The transmitted light is detected in the top medium (n3).

Using finite difference (FDTD) and Green's function methods, we calculate the transmission through this structure and studied the influence of an increase of the slab thickness on the localized surface plasmon wavelength.

We show that the resonance wavelength oscillates when the slab thickness increases. We developed a simple analytical model which allows to understand the origin of oscillations. We also study the influence of refractive indexes n1, n2 and n3 on oscillation parameters: period, amplitude, « average wavelength ».

8424-107, Poster Session

Novel nano-plasmonic splitter based on T-shaped Bragg grating waveguide

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Surface plasmon polaritons (SPPs) are propagating electromagnetic modes confined at a metal-dielectric interface surface which decay exponentially on both sides of the metal. They are considered as one of the promising techniques to overcome the diffraction limit and control sub-wavelength optical modes at the nano-scale domain. Recently, several plasmonic waveguide splitters have been proposed, for example, by introducing a wavelength selective element at the input side, so that the SPPs splitter can split the light in a predetermined direction. Another technique is that the direction of SPPs can be controlled through a metal-insulator-metal (MIM) waveguide modified by periodic and saw-tooth grooves. However, that structure suffers the disadvantages of a complex structural configuration and difficult fabrication.

In this paper, a novel T-shaped plasmonic MIM structure with one input and two outputs is proposed which uses simple stacked Bragg reflectors placed on both the left and right branches. The structure is analyzed by the finite-difference time-domain (FDTD) method. The resonance wavelengths of the structure are characterized by the scale of the photonic band gap (PBG) of the Bragg reflector. Our simulation results therefore demonstrate that the resonance wavelengths of the SPPs can be effectively controlled and guided along the desired direction with high confinement by proper selection of the structural parameters such as the refractive index of the dielectric and the period and the number of dielectric modulations N. We also show that the splitter ratio (the ratio of the power of the left and right output) and loss can be adjusted by changing the value of N. As N increases, the splitter output ratio decreases while the loss increases and hence the splitting ratio of the splitter can be designed by simply using different N.

8424-108, Poster Session

AgInS2-ZnS nanocrystals: probing the aging process by photon-EPR and photoluminescence

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The interest in semiconductor nanocrystals (NCs), with adjustable band gap energy has increase in the last decades due to their potential application in bio labeling light-emitting devices and solar cells. Most of the potential applications require that the nanocrystals present: i) high quantum yield values, ii) are free of toxic heavy elements such as Cd, iii) are stable in time and under irradiation. In this context in a first step AgxInxS2-Zn2(1-x)S nanocrystals with different compositions were prepared and characterized by different techniques such as TEM, XRD, EPR, UV-VIS absorption, Raman and photoluminescence (by steady state, time resolved modes and quantum yield measurements). In a second step the nanocrystals were irradiated with different excitation wavelengths and with different irradiation time and characterized again. The emission is characterized by a broad band composed of at least two components (previously assigned to surface and intrinsic states) that behave differently when irradiated under different excitation wavelengths. Interestingly one component presents an EPR signature that is fully reversible under illumination and the other component presents an EPR signature that is irreversible under illumination. The identification of the different contributions for the emission with different behaviours under illumination allowed a better understanding of the aging problem of the nanocrystals and above all open the door to adapt strategies to prevent it (or at least reduce it).

8424-109, Poster Session

Enhanced optical coupling in localized and band-gap characteristics of plasmonic nanostructure

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In this paper, we prepared the nanostructure with lamellar grating patterns by electron-beam lithography (EBL). The grating pattern is made of 100 nm thick Au on Si-Si3N4 substrate with an exposure area of 1.2×1.2mm2, after the e-beam evaporation Au metal grating with 50 nm and lift-off process as shown two different devices. The lamellar grating pitch size 500 nm of the pattern are Au(grating)/Alq3 and Photo Resist PR(grating)/Alq3, respectively. The spontaneous emission from fluorescent organic semiconductor material of tris-(8-hydroxyquinoline) aluminum (Alq3) was used to excite SPPs on metal interface. We can see that the maximum intensity of planar:PR(grating)/Alq3:Au(grating)/Alq3 devices is 1:2.5:3.5. However, the SP energy can be extracted as light by providing grating nanostructure. The interaction between organic/metal interfaces and SP can allow specific directional emission. The resultant emission intensity can have up to 3.5 times enhancement and the LSP coupling rate is about 80% on the Au-grating/Alq3 structure, it potential applications of such an active plasmonic emitter and fluorescence biosensor with enhanced resonance energy due to interactions on the organic/metal grating nanostructure.

Our experimental results showed that the different contributions of SPBG and LSP resonance with an Alq3 dipole to strong directional emission as well as enhanced intensity. This approach is suitable for plasmonic emitter applications and it makes variety of applications, including the development of fluorescence biosensor and organic light-emitting dioses.

8424-110, Poster Session

Iron oxide Fe2O3, Fe3O4 nanoparticles for antimicrobial photodynamic action

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The main goal was to study the sensitivity of microorganisms to action of Fe2O3 or Fe3O4 nanoparticles and LED blue (405 nm) light.

The bacterial strains used in this study were Staphylococcus aureus 209 P, S. simulans, Dermabacter hominis (isolated from maxillary sinusitis).

As blue light source LED with spectrum maxima at 405 nm (31.5 mW/cm2) was taken. The light exposure was ranged from 5 to 30 min.

It was shown that irradiation with blue light caused a decrease in the number of microorganisms treated with Fe2O3 of 25 - 94% and with Fe3O4 of 20 - 63%.

8424-111, Poster Session

Plasmonic sinks for the selective removal of long-lived states

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Long-lived states are a significant source of photobleaching and ground state depletion in organic molecules. They are also a limiting factor for the realisation of continuous wave organic semiconductor lasers. It is well known that metallic structures can modify the local photonic density of states, influencing both radiative and non-radiative decay pathways of excited states. We show that, by systematically determining the optimal size and shape of metallic structures, it is possible to design 'plasmonic sinks' which are effective in selectively quenching unwanted states. Using exact electrodynamics calculations, it is shown that silica core/Au shell plasmonic sinks can increase the decay rate of long-lived states by up to four orders of magnitude, as compared to their intrinsic decay rate, while leaving neighboring transitions unaffected. In the specific case of unwanted triplet states, we demonstrate that plasmonic sinks can reduce photobleaching and ground state depletion by at least two orders of magnitude. For the case of continuous wave organic semiconductor lasers we show that, under realistic device conditions, the achievable laser repetition rate can be increased by a factor equal to the triplet decay rate enhancement. Finally, by studying exiton diffusion in organic films, we demonstrate that the large diffusion length of long-lived states can be exploited to selectively quench these states on impact, an effect that acts concomitant with the long-range energy-selective quenching due to plasmonic sinks. This enables us to propose a scheme to determine the optimal density of plasmonic sinks in organic films.

8424-112, Poster Session

Influence of ellipticity of nanorods on both TPA of femtosecond laser pulse and transformation of pulse spectrum

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We consider the propagation of femtosecond pulse in medium with nanorods with taking into account the dependence of TPA from ellipticity of nanorods and transformation of pulse spectrum. The relation between the bandwidth of an absorption line and bandwidth of spectum of laser pulse is considered under the laser pulse propagation.

We found that under certain conditions the distortion of spectrum can be minimized by taking into account the detuning of centre of aborption line from central frequency of spectrum of laser pulse.

8424-114, Poster Session

Enhancement of QDs photoluminescence by localized surface plasmon effect of Au-NPs

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Localized surface plasmon resonance is one of promising features of Gold nanoparticles (Au NPs) which can enhance the optical emission of semiconductor quantum dots (QDs) near around. The QDs emission is influenced in two ways, thus the excitation rate is increased due to intensified electric field around Au NPs, and the quantum yield is increased by modifying radiative and non-radiative decay rates. Here we investigated the photoluminescence enhancement of CdSe/CdS/ZnS QDs in close proximity of a layer of Au NPs. It is observed that the QDs emission is enhanced and the lifetime simultaneously shortened. This behavior is attributed to the interaction of QDs excitons with the localized surface plasmon resonance of Au NPs. It is believed that the life time of QDs is affected by decreasing its amount, due to a good spectral overlap of Au NPs resonance band with the QDs emission and simultaneously the red shift of the emission spectrum. Size-dependent photoluminescence enhancement is figured out by immobilizing Au NPs in the 40-150 nm size range on glass substrates. The maximum enhancement is gained for 80 nm Au NPs. As it has been demonstrated, a proper spacer thickness is required to avoid any kind of quenching effect due to non-radiative energy transfer in short distances, therefore a layer of PVP polymer with different thicknesses coated on Au NPs. This applied to samples with different concentration of QDs in PMMA matrix. The role of excitation wavelength in enhancement is investigated upon exciting with different wavelengths. The enhancement is increased as the excitation wavelength gets closer to resonance wavelength of Au NPs. It is explained as a higher excitation rate in close to resonance wavelength. At the end, we reported more than 2-fold photoluminescence enhancement as CdSe/CdS/ZnS QDs used with large Au NPs. These results could be utilized for photonic applications like Bio-sensing and solar cells.

8424-115, Poster Session

Detecting the radial and azimuthal components of Laguerre Gaussian beams

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The last two decades have seen widespread interest in light fields possessing orbital angular momentum, which is associated with azimuthal phase variations within the light field. In particular the orthonormal basis set of Laguerre-Gaussian (LG) beams has been of interest in this regard. An LG beam is typically characterised by two indices, namely the azimuthal index L, which denotes the number of cycles of 2pi phase around the mode circumference and the radial index P where P+1 denotes the number of rings present within the light field. In addition to the fields of sub-diffractive imaging and optical manipulation, light fields with non zero azimuthal index are of central importance in quantum information processing. They permit access to a large multi-dimensional Hilbert space in contrast to the use of spin angular momentum (polarisation state) for such studies. Recently, multiple methods have emerged to measure the azimuthal index of a LG light field. These include the use of computer-generated holograms, rectangular slits, arrays of circular apertures, triangular and square shaped slits to name a few. All these methods are able to determine the azimuthal index of LG beams. However, these methods completely neglect the radial index P and work only for a pre-determined value such as P=0. Without the measure and knowledge of the radial index, it is impossible to correctly neither deduce the orbital angular momentum of a beam nor distinguish between an optical misalignment and a complex radial behaviour. Thus, it is crucial to appreciate the influence of both mode indices upon the far-field diffraction pattern of a diffracting mask. Here, we employ a set of triangular apertures and more generally random apertures to measure both the azimuthal and radial indices simultaneously. The method is generalised to include superpositions of LG beams and detect their relative amplitudes and phases.

8424-116, Poster Session

Fano interference in symmetry-reduced multi-arm plasmonic nanocrosses

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Successful development of localized surface plasmon resonance-based technologies (e.g. biosensing, plasmonic lasing) relies on a detailed control over the basic resonance characteristics - the resonance frequency, line width and line shape. Dipole activation of dark higher order modes and hybridization into anti-parallel oscillating dipole moments has emerged as one of the most promising methods to achieve line width and line shape tuning in plasmonic nanocavities. In both cases, the resulting subradiant modes are characterized by low radiative losses and, hence, narrow line widths. Spectral overlap with broader dipolar modes can furthermore result in destructive and constructive interferences with an asymmetric Fano resonance line shape. Typically, these coherent coupling effects are achieved in cavity designs consisting of two or more capacitively coupled nanoparticles [1,2].

Here, we show that a plasmonic nanocross geometry consisting of two or more conductively coupled nanobars, thus forming a single building-block nanocavity, can likewise support spectrally sharp Fano resonances in the visible and near infrared. Finite difference time domain calculations of absorption and scattering cross-sections, as well as charge density profiles, are used to reveal the nature of the different modes. Moreover, experimental spectra support these calculations.

The ability to posses discrete degrees of rotational symmetry situated between rotational invariance ($C\infty$), like a disk, and no rotational symmetry at all (C1), like a non-equilateral triangle, makes the nanocross a fundamentally interesting plasmonic structure. The nanocross' rotational symmetry is shown to have a crucial influence on the dipole activation of dark quadrupolar and octupolar modes. Particularly important about nanocross geometries with reduced symmetry, is the fact that they allow the excitation of Fano resonances without the need for nanometer sized interparticle gaps [3,4].

Our results for relatively simple nanostructures can form a basis for the design and understanding of new, more advanced plasmonic nanosystems.

[1] N. Verellen, Y. Sonnefraud, H. Sobhani, F. Hao, V. V. Moshchalkov, P. Van Dorpe, P. Nordlander, and S. A. Maier, "Fano resonances in Individual coherent plasmonic nanocavities"Nano Letters, 9(4), 1663-1667, 2009.

[2] B. Luk'yanchuk, N. I. Zheludev, S. A. Maier, N. J. Halas, P. Nordlander, H. Giessen, and C. T. Chong, "The Fano resonance in plasmonic nanostructures and metamaterials", Nature Materials 9, 707-715, 2010.

[3] N. Verellen, P. Van Dorpe, D. Vercruysse, G. A. E. Vandenbosch, and V. V. Moshchalkov, "Dark and bright localized surface plasmons in nanocrosses", Optics Express 19(12), 11034-11051, 2011.

[4] N. Verellen, P. Van Dorpe, C. Huang, K. Lodewijks, G. A. E. Vandenbosch, L. Lagae, and V. V. Moshchalkov, "Plasmon line shaping using nanocrosses for high sensitivity localized surface plasmon resonance sensing", Nano Letters 11(2), 391-397, 2011.

8424-117, Poster Session

InP/ZnSe/ZnS core-multishell quantum dots for improved luminescence efficiency

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Semiconductor quantum dots (QDs) exhibit unique optical properties like size-tunable emission color, narrow emission peak, and high luminescence efficiency. QDs are therefore investigated towards their application in light-emitting devices (QLEDs), solar cells, and for bio-imaging purposes. However, in most cases QDs made from cadmium compounds like CdS, CdSe or CdTe are studied because of their facile and reliable synthesis. Due to the toxicity of Cd compounds and the corresponding regulation (e.g. RoHS directive in Europe) these materials are not feasible for customer applications. Indium phosphide is considered to be the most promising alternative because of the similar band gap (InP 1.35 eV, CdSe 1.73 eV). InP QDs do not yet reach the quality of CdSe QDs especially in terms of photoluminescence quantum yield and peak width. Typically, QDs are coated with another semiconductor material of wider band gap, often ZnS, to passivate surface defects and thus improve the luminescence efficiency. Concerning CdSe QDs, multishell coatings like CdSe/CdS/ZnS or CdSe/ZnSe/ZnS have been shown to be advantageous due to the improved compatibility of lattice constants. Here we present a method to improve the luminescence efficiency of InP QDs by coating a ZnSe/ZnS multishell instead of a ZnS single shell. ZnSe exhibits an intermediate lattice constant of 5.67 Å between those of InP (5.87 Å) and ZnS (5.41 Å) and thus acts as a wetting layer. As a result InP/ZnSe/ZnS is introduced as a new core-shell quantum dot material which shows improved photoluminescence quantum yield (up to 75 %) compared to the conventional InP/ZnS system.

8424-119, Poster Session

Sensitivity enhancement of coupled plasmon-waveguide resonance sensors with optimization of gold-silver-alumina layers

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Coupling surface plasmon resonance (SPR) mode to waveguide mode(s) by simply forming a dieielctric layer on top of the metallic layer can improve the sensor's response to molecular variations. In this study, optimization of Coupled Plasmon - Waveguide Resonance (CPWR) sensors' layers to enhance their sensitivities is investigated. Optimizations of wavelength and thicknesses for highest sensitivities of the angularly interrogated CPWR sensors are accomplished with Fresnel's reflectivity equation and the full width half maximum calculations. Sensitivities are determined for three different film formations that consist of: (I) gold-alumina, (II) silver-alumina, and (III) gold-silver-alumina layers. Optimizations are achieved in the spectral and the dimensional domains in four steps: (1) Rough spectral scan: it is assumed that thicknesses of the CPWR sensor's layers are constant and the cover refractive index is equal to 1.33 for spectral domain calculations. They are carried out from 400 nm to 900 nm with 50-nm steps to obtain the rough optimal wavelength for the highest sensitivity. (2) Rough thickness scan: Thicknesses of metallic and dielectric layers are varied to calculate highest sensitivity at the wavelength. (3) The fine spectral scan: It is assumed that thicknesses of the layers are constant and sensitivity calculation with fine scanning steps ($\Delta\theta$ = 10 nm) around the wavelength is achieved to determine the wavelength for highest sensitivity. (4) The fine thickness scan: The final step for the optimization is to calculate thickness values for better sensitivity at the new wavelength. The sensitivities averaged for varying cover refractive index in the range of 1.33-1.39 are mapped around the optimum point of thickness combination as function of metallic and dielectric layer thicknesses at optimum wavelength. Results from our parametric study show that there is approximately 14-fold improvement in the sensitivity for optimized sensor designs by comparing with a typical SPR sensor. The highest CPWR sensor's sensitivity 720 RIU-1 is obtained at Lambda = 600 nm with the gold-silver-alumina layer combination.

8424-120, Poster Session

Polarised stimulated emission depletion dynamics following single- and two-photon excitation

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Polarised Stimulated Emission Depletion (STED) measurements are used to probe molecular alignment changes and population removal following both single and two-photon exciation. The efficiency of stimulated emission depletion depends on both the intrinsic molecular photophysics (e.g. the STED cross-section and ground state relaxation dynamics) and the orientation of the emission transition dipole moments in the laboratory frame. The degrees of transition dipole alignment created in single and two-photon excitation are fundamentally different. Both processes create different degrees of quadrupolar alignment as observed by fluorescence anisotropy. However two-photon excitation creates a higher degree of (hexadecapolar) molecular alignment, this is not observed in spontaneous emission but plays a significant role in the stimulated emission depletion (DUMP) process. In this work we make direct experimental comparisons between time-resolved single and two-photon excited stimulated emission depletion. Linear and circularly polarised two-photon absorption and fluorescence anisotropy experiments are used to characterise the transition tensor and thus determine the "hidden" degree of hexadecapolar alignment created by two-photon absorption. Time resolved stimulated emission depletion measurements are carried out in a collinear excitation-detection geometry to facilitate a direct comparison between the two excitation processes. Stimulated emission depletion is characterised by two experimental observables: the degree of population removal FD and the change in fluorescence anisotropy R. These are recorded for a fixed PUMP-DUMP delay and DUMP pulse-width as a function of DUMP energy. The population and anisotropy saturation data is analysed using a computer model of population and alignment dynamics in a strongly driven two-level system. Stimulated emission depletion dynamics are investigated for fluorescein in conditions of both slow and rapid rotational diffusion dynamics and with a varying PUMP-DUMP delay the relative contributions of quardupolar and hexadecapolar alignment are varied. Theoretical modelling is also used to predict the optimal conditions for stimulated emission depletion in two-photon excited states.

8424-122, Poster Session

Magneto-absorption in strongly oblate semiellipsoidal quantum dot

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Within the framework of adiabatic approximation the energy levels and direct interband light absorption in strongly oblate semiellipsoidal quantum dot in the presence of external magnetic field are studied. The dependence of energy levels' configuration on quantum dot's geometrical parameters and field intensities is analytically obtained in three regime of magnetic quantization. It has been demonstrated that increment of the energy levels occur depending on the geometrical parameters and decrement occurs in depending on the magnitude of magnetic field. The energy levels of electrons are shown to be equidistant and sublevels of "slow" levels are arranged on the levels of "fast" sublevels. Analytical expressions for the absorption threshold frequency in the regime of strong size quantization are obtained. Blues shift of absorption threshold have been observed depending on the value of magnetic field. Selection rules for quantum transitions are revealed. Obtained results have been compared with the cylindric quantum dot and quantum well of corresponding heights.

8424-124, Poster Session

Amplifying the figure of merit of phase sensitive refractive index sensing by coupling of propagating and localized surface plasmon resonances

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Localized surface plasmon resonances in metallic nanoparticles are known to be really sensitive to the polarization state of the incident electromagnetic wave which excites them. In this paper, we investigate the angle- and polarization dependence of localized surface plasmon resonances (LSPRs) in periodically ordered gold nanodisks on top of a continuous gold layer and a dielectric spacer. In previous work [1,2,3] we have investigated similar nanoparticles with a random distribution, and we have shown that the figure of merit (FOM) of LSPR based refractive index sensing could be boosted 6 times by taking into account the phase of the plasmon resonances in spectroscopic ellipsometry measurements. By measuring the phase difference between P- and S-polarized excitation of the electric dipole resonances in the nanoparticles, very narrow phase transitions can be observed at the centre frequency of the LSPR. These narrow phase transitions mark the spectral position where the electron cloud makes the transition from in- to out-of-phase oscillation with respect to the incident beam. By ordering the nanoparticles in periodic arrays the effects of inhomogeneous broadening could be largely suppressed, resulting in further line width reduction and even higher numbers for the FOM. The periodic disk array also acts as a grating which allows very efficient excitation of propagating plasmons on the bottom gold layer that interact with the LSPR modes in the gold nanoparticles. By scanning the incident angle, we tune the inter-particle coupling which allows to tune the Fano resonance that arises due to coupling between extended surface plasmons and the localized plasmon modes.

[1] K. Lodewijks et al., Nanoplasmonic Sensors and Spectroscopy Conference, Goteborg, Sweden (2011)

[2] K. Lodewijks et al., Metamaterials Conference, Barcelona, Spain (2011)

[3] K. Lodewijks et al., in preparation

8424-126, Poster Session

Metal nanoparticle and plasmon resonances in organic light emitting diodes and solar cells

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Surface plasmons are known as collective oscillations of the conduction electrons at a metallic interface. The phenomenon has been extensively studied in the fields of surface enhanced Raman spectroscopy, metal enhanced fluorescence, and non-linear optics.1-2 However, only limited research has been dedicated to its application in organic light emitting diode (OLED). Here we have fabricated a plasmonic OLED by incorporating silica coated silver nanoparticles (NPs) into the emitting layer of a phosphorescent organic light emitting diode (PHOLED), as shown in the schematic diagram Fig.

1. As a result, the luminescence efficiency of the PHOLED is significantly improved under low charge carrier injection level due to surface plasmon enhanced exciton formation probability. In contrast, the incorporation of uncoated bare silver NPs greatly suppresses luminescence of the PHOLED due to metal NPs induced luminescence quenching. A silica shell with thickness 13 nm or above coated on Ag NPs surface can avoid the luminescence quenching of the emitting molecules caused by Ag NPs.

So far metal nanoparticles (NPs) have been used in thin film silicon solar cell research successfully as the substitute of traditional inverted pyramid surface texture for light trapping. However, the application of metal NPs in organic solar cell research is not as successful as that in silicon solar cell. Although many works have been dedicated to organic solar cells incorporating NPs, none explicitly isolates the optical function of NP from its electronic function in organic solar cells due to the multiple roles played.

We designed a polymer solar cell with configuration shown in Fig. 2 from which we can investigate solely the optical functions of metal NPs in the solar cell. The incorporation of NPs underneath the active layer results in degraded performance due to massive light loss caused by Ag NPs scattering and absorption. In contrast, the incorporation of Ag NPs above active layers can harvest more sun light due to the fact that the surface plasmon of Ag NPs enhances the extinction coefficient of the active polymer layer and the back-scattering from Ag NPs improves the optical absorption path length in the active layer, thus solar cell power conversion efficiency (PCE) is improved. However, a direct contact of Ag NPs with active polymer results in exciton quenching, which compromises its enhancement effect on PCE. The best position to incorporate Ag NPs into the solar cell appears to be above the active layer, with a spacer layer which is PEDOT in our prototype.

References

1. F. Liu, G. Aldea, and J. M. Nunzi, J. Lumin. 130, 56 (2010).

2. J. M. Nunzi and D. Ricard, Appl. Phys. B 35, 209 (1984

8424-128, Poster Session

Flexible cavity imprinted PDMS templates for the creation of metal sphere to cuboid nanoparticle or nano-void arrays

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Patterning surfaces with nano-features is of paramount importance for new generation substrates in the field of nanobiophotonics. Spherical nano-particle1 or nano-void2 array architectures can be produced using colloidal sphere lithography which is extremely cost effective compared to photo-lithographic techniques. Significant effort has been devoted to creating metal films deposited over ordered arrays of spheres to create substrates capable of enhancing spectroscopic signals.3 By controlling the size of the templating sphere and metal deposition height, the surface plasmon of the resulting array can be tuned to suit a particular application. However, to date, studies on nanocavity arrays have focused on spherical or cylindrical structures and altering the spherical geometry of the nanofeatures of such arrays has not been explored.

We report the creation of flexible polymer templates, which can deliver control over the size and shape of the nano-features and can be used to fabricate either nano-particle or nano-void arrays in gold or silver. As is the case for conventional nanosphere lithography, the size of the templating sphere controls the dimensions of the nano-feature, but additionally the flexibility of the template allows for a variety of shapes, from spherical to elipitical to cuboid, to be fabricated. The control over the shape of the feature arises from the ability to stretch the template. The plasmon resonance of the resulting arrays is demonstrated to be influenced by the shape of the particles, which presents applications for surface spectroscopies such as Surface enhanced Raman or metal-enhanced fluorescence. In addition, as the nanostructured arrays are assembled on highly flexible polymer platforms the macroscopic curvature of the array can be easily changed which may be of significant value in an optical device. We demonstrate the creation of both convex and concave shaped NP arrays.

[1] C. L. Haynes and R. P. Van Duyne, J. Phys. Chem. B, 2001, 105, 5599.

[2] P. N. Bartlett, J. J. Baumberg, P. R. Birkin, M.A. Ghanem and M. C. Netti, Chem. Mater., 2002, 14, 2199;

[3] M. Litorja, C. L. Haynes, A, J. Haes, T. R. Jensen and R. P. Van Duyne, J. Phys. Chem. B, 2001, 105, 6907

8424-129, Poster Session

Principle, applications, evaluation and development of time lens: a review and outlook

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Based upon the parallel between the paraxial diffraction of beams through space and the dispersion of narrowband pulses through dielectric media in time, namely, space-time duality [1,2], time lens has been exploited over the last two decade to provide widely employment in Photonic fields of pulse magnification and generation, time to frequency conversion, optical packet and pulse compression and pulse shaping [3-18]. Time lens and Photonics techniques enhanced each other and even time lens itself is a milestone of the development of Photonics.

A time lens imposes a temporal quadratic phase modulation onto the incident light, analogous to a spatial lens imposing a spatial quadratic phase onto the wavefront. In practice, the quadratic phase modulation can be achieved approximately by applying a sinusoidal radio frequency (RF) signal to an electro-optic phase modulator [19-36] or employing some nonlinear processes including sum- & difference-frequency generation (SFG, DFG) [37-39], self & cross phase modulation (SPM, XPM) [40-42] and four-wave mixing (FWM) [43-48]. With proper dispersion, a temporal imaging system can be realized by time lens to achieved pulse magnification [39,40], compression [4,17,31,34] and time to frequency conversion [3,15,28].

Our motivation in this paper is to show how time lens can be exploited to develop practical instrumentation for ultrafast optical signal processing by triggering numerous literatures from the early 1990s to the present.

The paper is organized as follows: Firstly, state-of-the-art implementations of time lens by PM, SFG, XPM and FWM are summarized and analyzed by mathematic description. Then, limitations of different time lens described above for practical applications are analyzed, accordingly, based on the technical evaluation. Applications of time lens including pulse magnification and time to frequency conversion for ultrafast pulse measurement, are outlined, with the emphasizing on the quantitatively evaluation by performances including resolution and record length. Furthermore, some ultrafast nonlinear principle such as surface-plasmon enhanced ultrafast second- and third-order optical nonlinearities in metallic nanostructure [49-51], strong third-order optical nonlinearity induced high efficient FWM in Graphene [52-54] as potential theoretical and technological opportunities to developing time lens are presented and discussed.

8424-16, Session 4

Piezo-phototronic effect and its applications in flexible optoelectronics and energy

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Piezoelectricity, a phenomenon known for centuries, is an effect that is about the production of electrical potential in a substance as the pressure on it changes. Wurtzite structures such as ZnO, GaN, InN and ZnS, due to the polarization of ions in a crystal that has non-central symmetry, a piezoelectric potential (piezopotential) is created in the crystal by applying a stress. The effect of piezopotential to the transport behavior of charge carriers is significant due to their multiple functionalities of piezoelectricity, semiconductor and photon excitation. By utilizing the advantages offered by these properties, a few new fields have been created. Electronics fabricated by using inner-crystal piezopotential as a “gate” voltage to tune/control the charge transport behavior is named piezotronics, with applications in strain/force/pressure triggered/controlled electronic devices, sensors and logic units. Piezo-phototronic effect is a result of three-way coupling among piezoelectricity, photonic excitation and semiconductor transport, which allows tuning and controlling of electro-optical processes by strain induced piezopotential.

The objective of this talk is to introduce the fundamentals of piezotronics and piezo-phototronics and to give an updated progress about their applications in energy science (LED, solar) and sensors (photon detector and human-CMOS interfacing).

[1] Z.L. Wang “Piezopotential Gated Nanowire Devices: Piezotronics and Piezo-phototronics”, Nano Today, 5 (2010) 540-552.

[3] Y.F. Hu, Y.L. Chang, P. Fei, R.L. Snyder and Z.L. Wang “Designing the electric transport characteristics of ZnO micro/nanowire devices by coupling piezoelectric and photoexcitation effects”, ACS Nano, 4 (2010) 1234-1240.

[2] Y.F. Hu, Y. Zhang, Y.L. Chang, R.L. Snyder and Z.L. Wang “Optimizing the Power Output of a ZnO Photocell by Piezopotential”, ACS Nano. 4 (2010) 4220-4224.; Corrections: 4 (2010) 4962 - 4962.

[3] Q. Yang, W.H. Wang, S. Xu and Z.L. Wang* “Enhancing light emission of ZnO microwire-based diodes by piezo-phototronic effect”, Nano Letters, 11 (2011) 4012-4017.

[4] Q. Yang, X. Guo, W.H. Wang, Y. Zhang, S. Xu, D.H. Lien, Z.L. Wang* “Enhancing sensitivity of a single ZnO micro/nanowire photodetector by piezo-phototronic effect”, ACS Nano, 4 (2010) 6285 - 6291.

[5] Y. Yang, W.X. Guo, Y. Zhang, Y. Ding, X. Wang, and Z.L. Wang “Piezotronic effect on the Output Voltage of P3HT/ZnO Micro/Nanowire Heterojunction Solar Cells”, Nano Letters, in press

[5] W.Z. Wu, Y.G. Wei and Zhong Lin Wang , Adv. Materials, “Strain-gated piezotronic logic nanodevices “, Adv. Materials, 22 (2010) 4711.

[6] Wenzhuo Wu and Zhong Lin Wang* “Piezotronic nanowire based resistive switches as programmable electromechanical memories”, Nano Letters, 11 (2011) 2779-2885.

8424-17, Session 4

Interaction of pulse laser beam with colloidal nanoparticles

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In last decade laser processing is used very successfully for production of nanoparticles of different size, shape, morphology and chemical composition, and as a result with different optical, electromagnetic and chemical properties. Recently we developed a new method in which pulse laser technique permits to produce spherical monodisperse submicron particles for wide class of materials from metals to semiconductors and even isolators [1, 2]. To control this process more precisely, deeper understanding of the mechanism of particle interaction with laser beam is necessary. Particle heating-melting-evaporation model [3] can be applied successfully for this purpose. This model assumes that all the energy absorbed by particle from a laser beam is spending for thermal (heating, melting, evaporation) and chemical (decomposition) processes in the particle. Absorbed energy can be easily found if particle absorption cross section (or absorption efficiency) is known. The last value, in turn, can be calculated by Mie theory if complex refractive index of material is available. As the result, critical values of laser power (or laser fluence) can be calculated for different thermodynamical processes available in the system. Here we show the applicability of this model, demonstrate the results of such calculations - special “phase diagrams” where critical values of laser fluence are plotted as the function of particle diameter for each of the phase transition processes occurred in the system, and use these “phase diagrams” to discuss the mechanism of particle formation in different systems like noble metals, boron, silicon, titanium or copper oxides.

References:

1. H. Wang, A. Pyatenko, K. Kawaguchi et al., Angew. Chem. Int. Ed. 2010, 49, 6331.

2. H. Wang, N. Koshizaki, L. Li et al., Adv. Mater. 2011, 213, 1865.

3. A. Pyatenko, M. Yamaguchi, M. Suzuki, J. Phys. Chem. C, 2007,111, 7910.

8424-19, Session 4

Spontaneous emission in a cylindrical nanocavity: Ab initio analytical approach

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Control over spontaneous emission on a nanoscale is one of the challenging tasks of nanophotonics. As it has been known since the Purcell's report, the spontaneous emission rate can be significantly modified if an emitter is placed into a cavity. The widely used expression derived by Purcell gives only a rough estimate for the spontaneous emission enhancement factor in terms of the cavity mode quality factor and effective volume. A rigorous approach, however, requires the knowledge of the cavity mode spectrum and calculation of the transition rate to all allowed modes as a function of the emitter transition frequency and its position. Being applied to a cylindrical nanocavity, such an approach implies the proper determination of the Fabry-Pérot modes [1].

In the present work, we have derived an analytical approach for the dyadic Green's function of a cylindrical cavity of arbitrary diameter and length with arbitrary dielectric functions of both its interior and exterior. The approach is based on the introduction of fictitious surface currents on both end facets of the nanocavity. The solution of the wave equation with a point dipole source inside the cavity which satisfies all the necessary boundary conditions is found in terms of the Fourier integral over the propagation constant in a complex plane.

The field amplitudes which determine the dyadic satisfy a matrix integral equation which is reduced to a set of linear algebraic equations when the cavity length is much larger than its diameter. We have derived general expressions for the field susceptibility tensor and the spontaneous emission rate (the Purcell factor) inside such a cavity. In this approach, the transition rate fraction originated from decay into a specified cavity mode (the beta factor) is determined by the residue at the pole associated with this mode. The general theory is illustrated by the calculations for a dielectric nanowire surrounded by either a vacuum or a metal.

[1] V.G. Bordo, Phys. Rev. B 81, 035420 (2010).

8424-20, Session 4

Multipole contributions into resonant scattering of light by nonspherical nanoparticles using the discrete dipole approximation

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A new theoretical approach, allowing analyzing the role of multipole modes in the extinction and scattering spectra of arbitrary shaped nanoparticles, is developed in the framework of the discrete dipole approximation. The proposed method can be used to control separately the positions of different multipole resonances as a function of nanoparticle sizes and shapes. The main attention is given to the first multipole modes including magnetic dipole and electric quadrupole moments. The role of magnetic quadrupole and electric octupole modes is also discussed. The method is applied to nonspherical Si nanoparticles with multipole responses in the visible optical range, allowing a decomposition of single extinction (scattering) peaks into their constituting multipole contributions. It is shown by numerical simulations that it is possible to design silicon particles for which the electric dipole and magnetic dipole resonances are located at the same wavelength in the visible optical range under certain propagation directions of incident light. The method can directly be generalized to systems consisting of many dipole-like particles.

8424-121, Session 4

Surface enhanced coherent anti-Stokes Raman scattering on nanostructured gold surfaces

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Raman spectroscopy is a molecular finger-printing technique; however, its feebleness prohibits fast imaging applications. Non-linear coherent anti-Stokes Raman scattering (CARS) transitions can be stimulated by using pulsed (ps or fs) lasers. In CARS the signals are much higher compared to conventional Raman spectroscopy. The signals can be further enhanced by several orders of magnitude by performing CARS on optimized nanostructured surfaces permitting faster imaging and lower photodamage.

Over the past several years we have developed nanovoid surfaces which are fabricated by self-assembly of colloidal templates followed by electrodeposition. They have tuneable optical properties, due to plasmonic absorptions on the surface, which are easily controlled as a function of their geometry. Using nanovoid surfaces we have established that plasmon absorptions are crucial and result in large enhancements in surface-enhanced CARS (SECARS). CARS on our optimized nanostructured surfaces show enhancement of >105 over conventional CARS. Further we have been able to demonstrate the chemical selectivity of SECARS and utilize it for molecular imaging on plasmonic nanostructures. Having established the sensitivity of SECARS and its chemical selectivity we have employed it to image monolayers and the interaction of lipids with biomolecules. Our work demonstrates fast biomolecular imaging on nanostructured surfaces with SECARS and paves the way for Raman based single molecule spectroscopy.

[1] C Steuwe, CF Kaminski, JJ Baumberg and S Mahajan, Nanoletters (2011)

8424-21, Session 5

Nonlinear nanobubble-enhanced photoacoustic spectral imaging to break the spectral, diffraction, and detection limits

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Linear photoacoustic (PA) imaging demonstrated the ability to assess deep tissue by breaking through the optical diffusion limit. This presentation summarizes nonlinear phototothermal (PT) and PA spectral imaging to break through the spectral, diffraction, detection and other optical limits. Linear PT and PA methods are based on sequent combinations of optical, thermal, and acoustic effects. In nonlinear mode, laser-induced nano- and micro-bubbles near overheated absorbing nanoparticles provide significant (10-100-fold) PT and PA signal amplifications, with simultaneous sharpening of spatial and spectral PT and PA resonances. The principles and new applications of these nonlinear PT and PA techniques are discussed with focus on PT/PA spectroscopy, microscopy, and cytometry. Using tunable pulse lasers with fast spectral scanning, we demonstrated ultrasharp resonances up to a few nanometers wide in relatively broad plasmonic spectra of gold nanorods, gold nanoshells, golden carbon nanotubes, and quantum dot-carbon nanotube conjugates. The sharpening effects can make the absorption lines of the plasmonic nanoparticles, photonic crystals, metamaterials and even conventional dyes narrower independently of the initial narrowness of the line and the physical phenomena limiting their width and line shape. Applications include nonlinear microscopy beyond the diffraction limit, super resolution spectral hole burning techniques, in vivo time-resolved flow cytometry of circulating single nanoparticles and cells, multispectral imaging and multicolor cytometry using ultrasharp rainbow plasmonic nanoparticles without spectral overlapping their absorption spectra, and nano-theranostics (i.e., the integration of ultrasensitive diagnosis and multiplex PT therapy) of cancer, infections, and cardiovascular diseases.

REFERENCES

1. Zharov VP. Ultrasharp nonlinear photothermal and photoacoustic resonances and holes beyond the spectral limit. Nature Photonics, 2011; 5: 110-116.

2. Zharov V. Far-field photothermal microscopy beyond the diffraction limit. Opt Let, 2003, 28:1314-1316.

3. Kim J-W, Galanzha EI, Shashkov EV, Moon H-M, Zharov VP. Golden carbon nanotubes as multimodal photoacoustic and photothermal high-contrast molecular agents. Nature of Nanotechnology, 2009; 4: 688-694.

4. Galanzha EI, Shashkov EV, Kelly T, Kim J-W, Yang L, Zharov VP. In vivo magnetic enrichment and multiplex photoacoustic detection of circulating tumour cells. Nature of Nanotechnology . 2009; 12: 855-860.

5. Khodakovskaya MV, Silva Ke, Nedosekin DA, Dervishi E, Biris AB, Shashkov EV, Galanzha EA, Zharov VP. Complex genetic, photothermal, and photoacoustic analysis of nanoparticle-plant interactions PNAS. 2011; 108:1028-33.

8424-22, Session 5

Photonic nanobiosensors as advanced tools for diagnostics applications

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Ongoing changes in medical care for complex diseases and patients conditions are demanding novel technological diagnostic tools that could enable quick, accurate, reliable and cost-effective results so that appropriate treatments can be implemented in time, leading to improved clinical outcome. Photonic nanobiosensors based on evanescent wave detection have revealed themselves as the most promise candidates for achieving truly point-of-care devices. Advantages as miniaturization, extreme sensitivity, robustness, reliability, potential for multiplexing and mass production at low cost can be offered. For this reason, our work aims at the development of advanced nanophotonic biosensor devices able to handle and directly analyze minimum amounts of biological fluids without previous labeling procedure, detecting target molecules in their natural form, without alterations.

Different photonic biosensor technologies are pursued in parallel: nanoplasmonics and Silicon-based. We work towards the assembly of a point-of-care device by using novel bimodal silicon waveguide nanosensors in a multiplexed configuration, polymer microfluidics and nanometric diffractive grating couplers for light in-coupling. The micro/nanointerferometric devices have shown sensitivity close to 10-7 in refractive index units, which means an ability to discern, in a label-free scheme, concentrations of biological molecules at pM level.

We have demonstrated the suitability of our nanobiosensor devices as valuable tools for fast clinical diagnostics, as for the real-time analysis of DNA single mutations in cancer-related genes, detection of bacterial RNA, evaluation of hormone disorders directly in human urine or evaluation of patient´s allergy using dendrimers, among others.

8424-23, Session 5

Integrated prism-free coupled surface plasmon resonance biochemical sensor

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Surface plasmons resonance (SPR) is a well-known technique in biochemical analysis. The sensor architectures usually involve prism coupling of the excitation light beam in order to generate the plasmonic wave. Coupling and sensing regions are usually separate components that need to be closely fitted to avoid any trouble during the measurement; that is regularly achieved in commercial equipment using bulky mechanics. Here, we present an integrated approach avoiding this prism coupling technique; diffractive optical coupling elements (DOCEs) are integrated with the sensing region on the same chip.

The proposed configuration involves angular interrogation principle as with prism coupling scheme. The SPR sensor chip includes two diffraction gratings integrated with the SPR sensing zone. The surface plasma wave is excited using the first diffraction order of the input-coupler diffraction grating. The output-coupler diffraction grating provides the optical coupling between the reflected light beam and the optical detector. The sensor signal-to-noise ratio as well as the reliability of the optical coupling between its components is inherently limited by the diffraction efficiency of the used diffraction gratings. For this reason, metal-coated diffraction gratings with blazed profile were used for our experimental setup.

The theoretical analysis of the DOCEs design optimization procedure as well as the sensor design performance are demonstrated and compared with experimental results. The validity of the implemented setup was verified using different concentrations of ethylene glycol solutions.

An essential advantage of the presented sensor design concept is that its implementation involves a low-cost conventional grating replication and thin film physical deposition process that introduce an attractive alternative for lab-on-chip applications. In addition, the optical part of the sensor could be fabricated from lightweight and low-cost materials. Thus, this concept would perfectly suit for large-scale production of low-cost and reproducible SPR sensor chips for biochemical analysis.

8424-24, Session 5

Classification of antibiotics by neural network analysis of optical resonance data of whispering gallery modes in dielectric microspheres

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Recently, a number of evanescent wave optical sensors have been developed and used for refractive index detection in sensing systems. A novel emerging technique for the label-free analysis of nanoparticles and biomolecules in liquid fluids using optical micro cavity resonance of whispering-gallery-type modes is being developed. Several schemes of such a method have been developed. The most promising looks a scheme based on polymer microspheres fixed by adhesive on the evanescence wave coupling element.

The sensitivity of the developed scheme has been tested by monitoring the whispering gallery modes spectral shift. Water solutions of ethanol, HCl, glucose, vitamin C and biotin have been used. Particular efforts were made for an optimal geometry for micro resonance observation under extremely low power of tunable laser exciting resonance. It was demonstrated that optical resonance under optimal geometry could be detected under the laser power of less then 1 microwatt. Material of microsphere the most appropriate for microbial application was also under investigation. Resonance shifts of C reactive protein water solutions as well as albumin solutions in pure water and with HCl modelling blood have been investigated in developed experimental geometry. Introducing controlled amount of nano particles (50 nm in diameter glass gel solution) into microsphere surrounding was accompanied also by correlative resonance shift. The most attention was concentrated on development of a techniques for sensing and recognition of antibiotics of different generation.

We demonstrated that the only spectral shift can not be used for identification of biological agents by developed approach. So neural network classifier for biological agents and micro/nano particles classification has been developed.

Probabilistic neural networks, multilayer perceptron and back propagation neural networks are the mostly wide used in biomedical classification. The developed technique to determine parameters of solutions of the biological agents, based on whispering-gallery modes optical resonance are the following. While tuning the laser wavelength images were recorded as avi-file. All sequences were broken into single frames and the location of the resonance was allocated in each frame. The image was filtered for noise reduction and integrated over two coordinates for evaluation of integrated energy of a measured signal. As input data the following parameters were used: normalized resonance shift of whispering-gallery modes and the relative efficiency of whispering-gallery modes excitation. The last value can be interpreted as the intensity of resonant spectrum integrated over the free spectral range and normalized by the intensity maximum within this free spectral range. Other parameters such as polarization of excited light, “center of gravity” of a resonance spectra etc. are also tested as input data for probabilistic neural network. After network designing and training we estimated the accuracy of classification. The probabilistic neural network analyses allowed the classification of antibiotics such as penicillin and cephasolin with the accuracy of not less then 97 %.

Developed techniques can be used for lab-on-chip sensor based diagnostic tools as for identification of different biological molecules, e.g. proteins, oligonucleotides, oligosaccharides, lipids, small molecules, viral particles, cells and for dynamics of a delivery of medicines to bodies.

8424-25, Session 5

Graphene-based high-performance surface plasmon resonance biosensors

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Since their successful commercialization in the 1990s, surface plasmon resonance (SPR) biosensors have become a central tool for the study of biomolecular interactions, chemical detection, and immunoassays in various fields. SPR biosensors gain their place by offering unparalleled advantages such as label-free and real-time analysis with very high sensitivity. To further push the limits of SPR capabilities, novel SPR structures and approaches are being actively investigated. Conventional SPR typically relies on thiolated self-assembled monolayers (SAMs) on gold surfaces. Despite its widespread use, one of the limitations of this approach resides in the kind of functional thiolated molecules which can be synthesized and the follow- up reaction to bind the receptor. Furthermore, the susceptibility of the gold-sulfur bond to oxidation and photodecomposition is a real challenge for thiol chemistry. Currently, the new primary research focus using thiolated SAMs in connection with SPR is also oriented towards decreasing the number of surface reaction steps involved in bioreceptors linking. At the same time, there is a growing interest in the biosensing applications of carbon nanomaterials, notably carbon nanotubes and graphene. Here we experimentally demonstrate a graphene-based SPR biosensor. By incorporating a graphene layer to the conventional gold thin film SPR structure, its biosensing sensitivity is significantly increased. This is shown in a typical affinity biosensing experiment to measure the real-time binding kinetics of streptavidin-biotin. In addition to higher sensitivity, we also obtain a much higher signal-to-noise ratio without the slightest modification of the usual measurement setup. This implies that a considerably lower limit of detection can be made possible with the novel structure. Moreover, our graphene-based SPR biosensors do not require sophisticated surface functionalization schemes as in conventional SPR in order to function. Previous reports have also suggested that graphene might effectively prevent non-specific binding of biomolecules on the sensor surface. With relatively simple fabrication methods and large scalability, these combined distinctive advantages can enable future generation of high-performance SPR biosensors.

8424-26, Session 6

Generalized Snell’s Law in three dimensions and out-of-plane refraction with plasmonic phase discontinuities

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The introduction subwavelenght abrupt phase shifts along the optical path adds a new degree of freedom in the light wavefront control. By spatially tailoring the geometry of an array of optical resonators, one can introduce phase discontinuities using the phase shift response of optical resonators around their resonance frequency [1]. The control on the phase profile of the wavefront, allows the arbitrary molding of the light in any desired way. It has been shown that the design to implement this kind of control can rely in a wide range of resonators (from electro-magnetic cavities to nanoparticle clusters and plasmonic antennas) and that it can be exploited to create a new class of flat optical components [2]. Furthermore it was demonstrated that a spatially varying phase response leads to a new version of the reflection and refraction laws.

Fermat’s principle of stationary phase describes with a simple formalism the fact that the actual path taken by a light ray from one point to another is such that the variation of the accumulated phase is zero with respect to an infinitesimal variation of the path. This yield to the classical reflection and refraction laws used to describe the angles formed by the light directions. When a constant phase gradient is present at the interface between two media, the contribution due the surface has to be accounted in the accumulated phase, leading to a generalized version of the reflection and refraction laws [1].

Using an interface patterned with an array of optical antennas [3] and suitably designing their geometry one can introduce a phase shift on the optical path. In particular we use a V-shaped antenna design reliant on a double mode operation that gives a total control of the phase and amplitude of the light scattered to generate the desired wavefront. We show that when the phase gradient is oriented along an arbitrary direction with respect to the plane of incidence, the reflected and refracted beams actually are bent to a direction not included in the plane of incidence. The remarkable features of out of plane beaming can be controlled by varying the orientation of the phase gradient with respect to interface. We show that experimental results on the out of plane refraction are in excellent agreement with a three dimensional generalized law derived analytically.

We expect that the phase control made possible by suitably designed optical resonators will lead to the development of a new class of flat optical components such as planar lenses with high numerical aperture, flat polarization converters and flat phase plates including optical phased arrays.

[1] N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.P. Tetienne, F. Capasso, Z. Gaburro Science 334, 333-337 (2011)

[2] P. Genevet, N. Yu, F. Aieta, J. Lin, M. Kats, R. Blanchard, Z. Gaburro, F. Capasso in press Appl Phy. Lett.

[3] L. Novotny, N. van Hulst Nat. Photon. 5, 83-90 (2011)

8424-27, Session 6

Quasi-total funneling of light in high aspect ratio gold grooves

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Plasmonics structures allows to manipulate the electromagnetic field at the subwavelength scale and to design and realize subwavelength optical antennas. Numerous cutting-edge applications are based on such optical antennas like biosensing, gas sensing, photovoltaic or infrared photodetection.

Here, we experimentally demonstrate the total extinction of the reflectivity for a transverse magnetic polarized wave on a gold surface etched on

6% of its area by both narrow 150 nm and deep 2 microns grooves. These high aspect ratio metallic grooves were fabricated using a mold cast technique based on an electrolytic growth of gold. They exhibit two resonance peaks in the infrared corresponding to the first and second cavity modes inside the grooves. We also evidence the incidence-invariance of their spectral response, which undoubtedly shows the localized nature of the resonances.

Then, we unveil the funneling mechanism, which is namely responsible for the redirection and subsequent concentration of the incident energy flow from the surface toward the tiny apertures of the slits (lambda/70). Thanks to the decomposition of the electromagnetic field into its propagative and evanescent parts, we unambiguously show that the funneling is not due to plasmonic waves flowing toward the grooves, but rather to the magnetoelectric interference of the incident wave with the evanescent field. This evanescent field is mainly due to the resonant wave escaping from the groove.

[1] P. Bouchon et al., Appl. Phys. Lett, 98, 191109 (2011)

[2] F. Pardo et al., Phys. Rev. Lett., 107, 093902 (2011)

8424-28, Session 6

Fabrication and optical stability of silanized gold nanorods as multifunctional transducers of near infrared light

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We provide novel insight into multifunctional nanoparticles with light extinction in the therapeutic window, optical stability and extensive possibilities of bio-conjugation with biopolymers and ligands. Over recent years, intense interest for innovative near infrared (NIR) dyes for mini invasive biomedical applications has driven the advent of noble metal nanoparticles with relevant plasmonic oscillations. In this context so-called gold nanorods have been proposed as excellent contrast agents for dark field, multiphoton luminescence, and photoacoustic microscopy, and sensitizers for photothermal microsurgeries and drug delivery. Moreover gold nanoparticles prove suitable for bio-conjugation e.g. to gain specificity for phenotypical anomalies of interest. As a genuine boundary effect, the plasmonic oscillations of noble metal nanoparticles become modified with their environment and biological interface. Factors which may play a role and disrupt the plasmonic bands include the aggregation (e.g. inside endocytic vesicles) and shape transformation of the particles, which may occur in a biological environment and under excitation.

The silanization of gold nanorods is proposed as a possibility to overcome these issues. A shell of porous silica confers isolation from the environment and additional stability, and also proves suitable for PEGylation and bio-conjugation with e.g. peptides and vitamins, which is discussed in detail. In particular we challenge the optical stability of these hybrid nanoparticles by engineering of models of aggregation in cells and biopolymers. While in the absence of silica gold nanorods undergo substantial degradation of their plasmonic oscillations, silanization proves excellent to maintain pristine optical properties even after critical flocculation.

8424-29, Session 6

The plasmonic rainbow effect: separating wavelengths at the nano-scale

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Plasmonic technology relies on the coupling of light to surface modes at metal-dielectric interfaces as well as waveguiding metallic structures. The advantages of such surface modes, the so-called surface plasmon polaritons (SPPs), have been demonstrated in subwavelength field confinement, bio- and chemical sensing, solar cells, enhancement of nonlinear effects to name but a few. While some of the applications make use of the resonant nature of surface polaritons, for others their broadband characteristics are important. While plasmonic devices in general can support SPPs in a broad spectral range below the surface plasma frequency, it is difficult to achieve efficient excitation of SPPs simultaneously at different wavelengths.

Non-resonant excitation via diffraction of individual surface feature is not efficient or directional, while the resonant structures, e.g., diffraction gratings have increased efficiency but with limited bandwidth due to their narrow resonant nature. Here we demonstrate unidirectional and broadband plasmonic antenna based on chirped plasmonic gratings. Near-field optical measurements have been used to visualise the excitation and focusing of SPP waves by the device as well as mode formation within the aperiodic structure. The weakly aperiodic structure allows for the formation of a trapped rainbow-type effect in a two-dimensional geometry as SPPs of different colours are coherently excited in different locations over the plasmonic nanostructure. This original approach opens up new opportunities for building unidirectional broadband plasmonic couplers that could be used for sensing purposes, information processing as well as photovoltaic applications for example.

In addition to far-field spectroscopy, the use of the newly implemented hyperspectral SNOM (Scanning Near-field Microscopy) technique allows us to obtain the full spectroscopic information at every point of the near-field image, and therefore to study the near-field behaviour of both periodic and chirped structures and compare them with numerical simulations results in order to fully understand the physical mechanisms involved.

8424-125, Session 6

Silver-poly(vinylidene fluoride-trifluoroethylene) nanocomposites: plasmon-polariton oscillations and ferroelectric poling behavior

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Composites consisting of metal nanoparticles dispersed in a polymeric matrix are of great interest for basic research as well as for different kind of applications e. g. in electronics and opto-electronics. The reason is the controllable surface plasmon oscillations while the absorption bandwidth can be tuned within a broad spectral range from near ultraviolet to infrared wavelengths. This forces the material optimization for applications such as infrared photodetectors and pyroelectric sensors.

Here, we demonstrate the synthesis of silver (Ag) nanoparticles, the preparation of thin composite films and the evaluation of their optical and electrical properties. The synthesis of nanoparticles is carried out in situ in the solid polymer matrix. Composite films are prepared by mixing the solved matrix polymer poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE)) and the silver precursor solution, evaporating the solvent thermally and performing an UV-irradiation in order to generate silver nanoparticles. Finally, Ag-P(VDF-TrFE) nanocomposites with silver mass fractions up to 30 wt.% are prepared and characterized.

Significant surface plasmon oscillations are found while the oscillation strengths depend on the amount of silver in the composite. Based on the effective particle size and silver mass fractions, the light absorption shows a broad bandwidth covering the UV, visible and infrared spectral range. A polarization build-up is caused either by a corona discharge or by applying the electric field in direct contact. Surface potentials after charging and polarization - electric field hysteresis curves are measured in order to determine and explain the resulting polarization in the Ag-P(VDF-TrFE) composites. The ferroelectric polarization is also proven by measuring the electro-active properties, especially the piezoelectric activity. In summary, the prepared Ag-P(VDF-TrFE) nanocomposites show multifunctional properties: a highly tunable visible as well as

infrared absorption is achieved by embedding Ag particles, whereby the polarization of the ferroelectric matrix polymer is still addressable.

8424-31, Session 7

Nanoplasmonic sensing for nanomaterials science

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Nanomaterials (particles and films) exhibiting a particular function are the core of a myriad of envisioned novel technologies and devices. These include, but are by far not limited to, sensors, heterogeneous catalysts, solar energy harvesting devices, photocatalysts, electronic and photonic devices, batteries and hydrogen storage systems. The successful exploitation of such nanomaterials requires the correlation of details in nanoparticle size, structure and local chemistry with the targeted functionality. The latter remains, however, a significant experimental challenge to this day for two general reasons.

The first one relates to the fact that the only fully satisfactory way to acquire such information is by the use of real time in situ spectroscopy. The latter is, however, experimentally very tough, in particular in harsh environments (high temperatures and pressures, reactive environments, etc.) such as those typical for, e.g., heterogeneous catalysis or hydrogen storage applications and relates to the well-known material (structure) and pressure gaps in catalysis.

The second one relates to unwanted “artifacts” and averaged response as always present in ensembles of sample nanomaterial and mainly caused by inhomogeneous size-distributions, as well as differences in the local chemistry and the local structure/geometry of (quasi-identical) nano-entities in the ensemble.

In this talk the potential of nanoplasmonic sensors exploiting both direct [1,2] and indirect sensing scheme [3,4] to scrutinize processes in and on the surface of nanomaterials in situ and in real time will be discussed for catalysis and hydrogen storage-related applications. Particular focus will be put on the unique possibility to use indirect nanoplasmonic sensors to study single functional nanoparticles [5,6] in situ and in harsh environments. The latter will be illustrated on a study of the hydride formation thermodynamics of single Pd and Mg nanoparticles [5].

1. Zoric, I.; Larsson, E. M.; Kasemo, B.; Langhammer, C. Advanced Materials 2010, 22, (41), 4628-4633.

2. Tang, M. L.; Liu, N.; Dionne, J. A.; Alivisatos, A. P. Journal of the American Chemical Society 2011, 133, (34), 13220-13223.

3. Langhammer, C.; Larsson, E. M.; Kasemo, B.; Zoric, I. Nano Letters 2010, 10, (9), 3529-3538.

4. Larsson, E. M.; Langhammer, C.; Zoric, I.; Kasemo, B. Science 2009, 326, (5956), 1091-1094.

5. Shegai, T.; Langhammer, C. Advanced Materials 2011, 23, (38), 4409-4414.

6. Liu, N.; Tang, M. L.; Hentschel, M.; Giessen, H.; Alivisatos, A. P. Nature Materials 2011, 10, 631-636

8424-32, Session 7

On the use of plasmonic nanostructures for the design of active nanodevices

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The design of active nanodevices present one of the great challenges scientists face to date. Plasmonic materials, which prove particularly suitable for passive devices, also show unique potential in the development of active functionalities

needed in the production of light sources, transistors, or energy cells. These novel materials are expected to overcome the speed of photonic devices with the nanoscale dimension of semiconductor electronics, opening a new technological era not constrained by the limitations in size and speed photonics and electronics devices show.[1]

In this presentation we will discuss the potential of complementary plasmonic structures made of assemblies of strongly interacting nanorods[2] as well as plasmonic crystals[3] in providing effective solutions in the development of active nanodevices.

References

[1] M. L. Brongersma and V. M. Shalaev, Science 328, 440 (2010).

[2] G. A. Wurtz, R. Pollard, W. Hendren, et al., Nature Nanotechnology 6, 107 2011).

[3] G. Wurtz and A. Zayats, Laser and Photon. Rev. 2, 125 (2008).

8424-33, Session 7

Plasmonic detection of single non-absorbing proteins using a gold nanorod

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Most methods capable of detecting a single molecule rely on the fluorescence or absorption of the molecule or of a label attached to the molecule. However, most (bio)molecules are purely refractive in the visible spectrum. Metal nanoparticles provide a means to detect these non-absorbing molecules. The electric field associated with a surface plasmon resonance (SPR) decays rapidly from the surface of the particle, into the surrounding medium. A perturbation of the local refractive index causes a shift of the SPR, allowing for the label-free detection of purely refractive molecules. The most sensitive plasmon sensors to date detect single molecules only when the plasmon shift is amplified, for example by labeling the analyte with a secondary nanoparticle. Here we demonstrate the plasmonic detection of single non-absorbing molecules without the need for labeling or amplification. By monitoring the plasmon resonance of a single gold nanorod using photothermal microscopy we observe single-molecule binding events in real-time with an integration time of 100 ms. We believe this is the first optical technique that detects single molecules purely by their refractive index, without any need for photon absorption by the molecule. The small size, bio-compatibility and straightforward surface chemistry of gold nanorods as nanosensors makes them promising for many biophysical problems, and may open the way to the selective and local detection of purely refractive proteins in live cells.

8424-34, Session 7

Plasmon dumping in Ag-nanoparticles/polymer composite for optical detection of amines and thiols vapours

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In this work we report the use of plasmon dumping to achieve optical detection of different organic molecules in liquid and in vapour phase. The optical sensor has been obtained by the development of a silver nanoparticle/polymer nanocomposite. An interesting property of the nanocomposite is that its matrix is based on a photosensitive compound which allows ultra-violet (UV) lithography and can be patterned with a resolution determined by the host. The photoresist is based on DNQ-novolac as the polymer matrix, and Ag(I) salts as the nanoparticle precursors. After UV lithography, silver nanoparticles are in situ synthesized inside the polymer patterns due to the reduction of the precursor ions during thermal treatment. The resulting structured nanocomposite shows a characteristic optical absorbance spectrum related to the localized surface plasmon resonance (LSPR) of the synthesized noble metal nanoparticle s. This fabrication technique is a fast, simple and non-expensive approach to the formation of extended polymer patterns with embedded silver nanoparticles. Moreover, the material constitutes a mechanism to position nanometric particles in the range 5-40 nm with resolution limited by the UV lithography, which represents a useful tool for nanoscience. By using this nanostructured plasmonic material, the detection of amines and 2-mercaptoethanol molecules has been achieved, both in dilution in water and in vapour phase. The sensing mechanism is based on the plasmon dumping related to the binding of the organic molecules at the surface of the nanoparticles, which produces a colour change that can be appreciated with the naked eye. This nanocomposite constitutes a platform for the fabrication of colorimetric arrays of bio/chemical sensors.

8424-35, Session 7

Second harmonic generation hotspots for switching and sensing applications in plasmonic nanostructures

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In metallic nanostructures, light can collectively excite surface electron waves, a property referred to as surface plasmons. Surface plasmons have the same frequency as light, but much shorter wavelengths, which allows their manipulation at the nanoscale. This emerging nanotechnology could find applications ranging from optical computing, through molecular sensing to invisibility. For all of these applications, gaining control of the plasmonic patterns in the nanostructures requires practical nanophotonic visualization methods.

Second Harmonic Generation (SHG) microscopy is a surface/interface sensitive optical technique that can be readily employed for the visualization of surface plasmons. The technique makes use of ultrafast laser pulses, which combine high peak laser intensity, for high SHG signals, with low average laser intensity, for low sample damage. Under the influence of the electric field of light, in plasmonic nanostructures, the regions of highest local field enhancements, or hotspots, can be driven in the nonlinear regime and become local SHG sources.

We made use of SHG microscopy to show that the hotspots at the terminals of U-shaped nanostructures made of gold can be switched in four distinctive logical states depending on the polarization of incoming light. Upon coupling the output extremities of these U-shaped switches to plasmonic metamaterial waveguides, we believe that information can be channeled through an all-optical circuit. Moreover, in square-ring nanostructures made of gold, we demonstrate that circular polarization can lead to homogeneous plasmonic field enhancements on the surface of the samples, i.e. no hotspots. These non-localized field enhancements can find applications in molecular sensing.

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8424-36, Session 8

Bridging classical and quantum plasmonics

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When two metallic nanoparticles are closely located to each other, a strong Coulomb interaction between the surface charge densities induced at each particle is produced. This situation supports the existence of a highly localized Bonding Dimer Plasmon (BDP) that results in a huge field enhancement at the interacting gap between the particles. This structure can be used as a canonical building block to sustain a variety of complex physical phenomena such as non-linear effects, quantum tunneling or photoemission, to cite a few. As the control of sub-nanometer separation distances is technological feasible, a classical description of the metal surface, based on the assumption of an abrupt change of the electron density at the surface of the metallic material, fails to correctly describe the optical response of a gap antenna. To account for the effect of the spill-out of the electrons at the surface of the metal, full quantum mechanical calculations have been developed with use of techniques such as time-dependent density functional theory (TDDFT). Since plasmonic nanostructures are usually large, a full quantum description of the optical response of standard plasmonic systems is not possible due to the huge number of electrons involved in the response. We present a new method to calculate quantum effects in large plasmonic systems based on parametric inputs derived from simpler full mechanical calculations. This quantum effective model is based on the description of the tunneling gap by means of a local dielectric function that depends on the quantum mechanical conductivity between the particles for each separation distance. Both the amplitude and the damping associated with the transmission probability of the electron are key to correctly construct the local dielectric function at the gap. Our results of the optical response in small systems agree perfectly with full quantum calculations and allow us for a complete description of the modal redistribution and collapse of the field enhancement in subnanometer gap-antennas formed by large structures. With this quantum effective model (QEM), we bridge a gap between classical and quantum plasmonics.

8424-37, Session 8

Surface plasmon polariton modulator with optimized active layer

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We study a metal-dielectric-metal waveguide as a surface plasmon polariton absorption modulator. A multilayered core consists of silicon nitride layer and ultrathin active layer embedded between two silver plates that serve as electrodes. We utilize a transparent conducting oxide, namely the indium tin oxide (ITO), as an ultrathin layer with the varied carrier density. The carrier density in the transparent conducting oxide layer changes according to the Thomas-Fermi screening theory under applying voltage to electrodes. In turn it changes effective plasma frequency of the layer. We employ analytical solutions for a multilayered system as well as numerical simulations with the commercial software package CST Microwave Studio in the frequency domain. We explore various anneal conditions to achieve different permittivity of the ITO. To advance the modulator design, namely to increase transmittance and enhance modulation depth or efficiency, we propose to substitute the continuous active layer by a 1D periodic grating. Different ways of patterning are considered, including periodic and disordered. Dependence from the pattern size and filling factor of the active material are analyzed for tuned permittivity of the ITO layer. Direct simulation of the device functionality validates optimization design.

8424-38, Session 8

Infrared spectral filtering based on guided-mode resonance structure

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We present an experimental study of bandpass filter based on a metallo-

dielectric guided mode resonance structure [1]. The structure consists of a gold grating deposited on a silicon nitride membrane (SiNx). The grating is designed so as the eigenmodes of the thin dielectric layer can be excited through diffracted orders. At the resonance, incoming energy is trapped in the waveguide and transmitted into the 0th-order thanks to a second coupling with the sub-wavelength metallic grating. Such a structure can be used for either polarized (1D grating) or unpolarized light (2D grating). Transmission peak and FWHM (Full Width at Half Maximum) can easily be tuned by changing the grating period and the slits size.

We fabricated a 1D structure for a demonstration in the infrared. We obtained both a spectral filter and a polarizer. A high transmission (~ 79% at a wavelength of 3.2 µm) was achieved, which represents an eight-fold enhancement of the geometrical transmission (grating period 2110 nm, slits width 200 nm, gold thickness 100 nm and SiNx layer thickness 650nm). Angle-resolved transmission measurements were performed with a Fourier-transform infrared spectrometer and revealed Fano-type resonances. We demonstrated that this Fano resonance is the result of interference between two transmission channels: a direct transmission and a resonant transmission via the eigenmode of the thin-film. Besides measured spectra show a good agreement with calculations based on the B-Splines Modal Method [2]. The small discrepancies are attributed to fabrication imperfections (surface and wall) and a misappreciation of the permittivity of materials.

Thanks to their intrinsic properties (high efficiency, tunability, extinction ratio), such structures could be used for multispectral imaging applications [3, 4] and a new generation of filters array is proposed.

References :

[1] E. Sakat et al., “Guided mode resonance in subwavelength metallodielectric free-standing grating for bandpass filtering”, Opt. Lett., 36(16):3054-3056, Aug 2011.

[2] P. Bouchon et al., “Fast modal method for subwavelength gratings based on b-spline formulation”, J. Opt. Soc. Am. A, 27(4):696-702, Apr 2010.

[3] R. Haïdar et al., “Free-standing subwavelength metallic gratings for snapshot multispectral imaging”, Appl. Phys. Lett., 96(22):221104, 2010.

[4] S. Collin et al., “Nearly perfect fano transmission resonances through nanoslits drilled in a metallic membrane”, Phys. Rev. Lett., 104(2):027401, 2010.

8424-39, Session 8

Near-field optical properties of Au-nanocubes: confinement of hot and cold spots

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We studied the near-field optical properties of colloidal gold nanocubes (GNCs) using a photochemical imaging method. This method is based on the vectorial molecular displacements, of photosensitive azo-dyes, which are sensitive to the polarization of the optical near-field of the GNCs. We analyzed the spatial confinement of both electromagnetic hot and “cold” spots with a spatial resolution up to 10nm (λ/50). The new concept of cold spot presents valuable and complementary electromagnetic information to the well known electromagnetic hot spot. We demonstrated that cold spots are highly sensitive to polarization and can be much more confined than hot spots enabling them to be applied in high resolution imaging and spectroscopy.

8424-40, Session 8

Plasmonic nanosensors in the treatment of cancer: an attempt to conquer the immortal illness

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In 2010, a survey conducted all over the world says that more than 7 million humans around the world died of cancer. One in three women and one in two men developed cancer during their lifetime. About 15 percent of all deaths worldwide, was attributed to cancer. In some nations, cancer will surpass heart disease to become the most common cause of death. This paper attempts to demystify the behaviour of cancer-the defining plague of our generation. Here, we present a novel method based on silver nanoparticle-generated transient photothermal vapour nanobubbles. These intracellular plasmonic nanobubbles are effective in the diagnosis (by optical scattering) and treatment (by mechanical, nonthermal and selective destruction of target cells) of cancerous cells. Theoretical simulation of fused silica rod SPR sensors and optical fiber SPR sensors was carried out. Then these nanosensors were designed, fabricated and their sensitivities were measured experimentally. We introduce the nanosensors and describe how its size and environment can be harnessed to detect and treat cancer cells. This paper has been written from the quest to launch something that can eradicate this disease from our bodies and societies forever.

Here, sensing application of Surface Plasmon Resonance (SPR) technique has been utilized.The excitation of surface plasmons at metal/dielectric interface results in transfer of energy from incident light to surface plasmons, thereby reducing the intensity of reflected light. If the intensity of reflected light is measured as a function of angle of incidence,then a sharp dip is observed at resonance angle.Then, SPR-based fiber optic nanosensors were fabricated by removing the silicon cladding from middle of the fiber and the unclad core was coated with Ag layer.Sensitivity of the nanosensors was then tested by changing the dielectric. It showed change in resonance angle.

For diagnosis of cancer,we put forward an innovative model where Plasmonic nanobubbles (PNB) can be generated by interacting optical radiation with nanoparticles coated on the nanosensors. When a plasmonic nanoparticle is activated by a laser pulse, it acts as a heat source and generates a transient PNB in its surrounding environment. PNBs of nanometer-scale size and nanosecond-scale duration are well suited as diagnostic probes by scattering light from the probe laser.

For remedial purposes of cancer,PNBs provide localized therapeutic action through a mechanical, non-thermal impact due to their rapid expansion and collapse, thereby disrupting the cell membrane.

PNB’s provide an efficient technique to diagnose and treat cancer without any use of chemicals and relying only on nanoscale phenomena of light and heat which are natural to living systems. The combination of photothermal properties of plasmonic nanoparticles with those of transient vapour bubbles can be used to diagnose and treat cancer in a single method, making the treatment shorter and more efficient.

8424-41, Session 9

Ultrafast nanoplasmonics with optical antennas

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Metal nanoantennas have been demonstrated to work as optical analogues to their well-known counterparts at radio and microwave frequencies. They are designed to increase the interaction of light with single nanoemitters, such as molecules, semiconductor quantum dots, or color centers in diamond. We present a “tunable” nanoantenna by changing its length and feedgap via precise nanomanipulation with the tip of an atomic force microscope [1] and investigate the nonlinear optical properties of these metal nanosystems [2]. Using few-cycle femtosecond light pulses and sub-wavelength imaging, we demonstrate 4-dimensional light confinement [3]. We show that antennas operating in the infrared

are truly radiation-damped systems. Our investigations open the door for future tailoring of single metal nanoantennas for ultrafast and nonlinear applications. Consequently, such structures will be attractive tools for new classes of experiments in the field of femtosecond quantum optics with solid-state single-electron systems [4].

References:

[1] J. Merlein et al., Nature Photon. 2, 230 (2008).

[2] T. Hanke et al., Phys. Rev. Lett. 103, 257404 (2009).

[3] T. Hanke et al., submitted (2011).

[4] F. Sotier et al, Nature Phys. 5, 352 (2009).

8424-42, Session 9

Realization of hybrid systems coupling molecules and gold nanoparticles towards fluorescence enhancement

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Two photon induced fluorescence (TPIF) microscopy is a technique commonly used by biologists for analytical diagnostic applications. However, currently available biomarkers present poor two photon brightness characteristics, which limit the performance of the TPIF microscopy. Our objective is to study the conditions to get benefit of the plasmonic properties of gold nanoparticles (NPs) to enhance fluorophores emission through nanoantenna or Purcell effects.

As a first step, the TPIF of colloidal gold nanoparticles having similar sizes but exhibiting different forms was investigated (spheres, rods, cubes and triangles). Experiments were performed in aqueous solutions using a Ti-Sapphire laser source emitting 100 fs pulses in the 750-950 nm wavelength range. We show that whatever the excitation wavelength, nanorods happen to exhibit the highest TPIF signal. Detailed investigation of the TPIF signal dependence with the excitation wavelength was performed. In the case of nanorods, we observe that the maximum TPIF signal is located at the NPs surface plasmon resonance wavelength, pointing the role of increased absorption rate in the observation of increased TPIF. Further investigations are currently under way in the case of single nanorod immobilized onto previously treated ITO coated glass substrates, varying the polarization of the laser excitation beam. For this purpose an AFM platform was recently coupled to our TPIF microscopy set-up, enabling joint optical and topographic measurements of single nanoobjects.

Next step will also consist in applying the layer by layer deposition technique in order to control the realization of hybrid systems coupling molecules and particles at varying distances. First measurements seem to indicate the existence of a specific distance allowing TPIF enhancement. A more detailed study considering the intensity and lifetime of such hybrid system is currently under way in order to fully understand the signal enhancement origin.

8424-43, Session 9

Engineering the optical properties of single epitaxial GaAs quantum dots using optical antennas

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Coupling single quantum system to artificial nanostructures allows engineering the optical properties of the emitters. Plasmon resonant structures are particularly interesting as the electromagnetic field associated with them is localized on a subwavelength scale resulting in modified light-matter interaction. This has allowed controlling, e.g., the excitation and emission rate [1] as well as the emission pattern of a single emitter [2].

We have experimentally investigated using plasmon resonant nanoantennas to enhance the photoluminescence properties of individual epitaxial semiconductor quantum dots [3]. As nanoantennas we use chemically synthesized spherical gold nanoparticles and lithographically fabricated structures. The emitters are epitaxially grown AlGaAs/GaAs quantum dots which are buried a few nanometers beneath the semiconductor surface and photoluminesce at approximately 760 nm wavelength [4]. The advantage of this system is that the optical properties of the quantum dots are very stable and the transition dipole moments have a fixed orientation. The thin barrier layer allows efficient coupling between the quantum dot and an optical antenna positioned above the emitter. The position of a quantum dot can be determined with high precision from a characteristic feature in the surface topography above each quantum emitter using atomic force microscopy (AFM) or scanning electron microscopy.

In the first part of our study we have applied AFM based nanomanipulation to position 90 nm diameter gold nanoparticles above individual quantum dots. The particles act as optical antennas resonant to the incident light field enhancing the excitation rate of the emitters. Using low-temperature confocal photoluminescence microscopy we observe an increase in the photoluminescence of up to a factor of 8 due to the nanoantenna [3]. Based on time-resolved measurements and spectral analysis of the photoluminescence, we can attribute the enhancement in luminescence to an increase in the local optical excitation power density in the vicinity of the quantum dot. The optical antenna also results in a slight spectral-narrowing of the emission. In the usual far-field excitation scheme carriers are generated in a larger volume than when the nanoparticle is used. This leads to fluctuating charges, broadening the dot's emission by spectral diffusion.

In order to enhance the emission from the quantum dots we have fabricated metal nanorods on the semiconductor surface using electron beam lithography. By varying the aspect ratio of the rod, the spectral position of the transverse and longitudinal plasmon resonances can be tuned. We observe significant modifications in the photoluminescence from quantum dots decorated by a resonant nanoantenna. In particular, the elongated nanoantenna results in a strong polarization anisotropy of the emission. We have also taken first steps in realizing integrated plasmonic nanocircuits containing single quantum emitters. Our work demonstrates that controlled coupling between epitaxial quantum dots and plasmonic nanostructures is a promising route to realizing nanoscale optical circuits making use of single photon emitters.

References

[1] A. Kinkhabwala, Z. Yu, S. Fan, Y. Avlasevich, K. Müllen, and W. E. Moerner, "Large single-molecule fluorescence enhancements produced by a bowtie nanoantenna," Nature Photonics 3, 654-657 (2009).

[2] A. G. Curto, G. Volpe, T. H. Taminiau, M. P. Kreuzer, R. Quidant, and N. F. van Hulst, "Unidirectional Emission of a Quantum Dot Coupled to a Nanoantenna," Science 329, 930-933 (2010).

[3] M. Pfeiffer, K. Lindfors, C. Wolpert, P. Atkinson, M. Benyoucef, A. Rastelli, O. G. Schmidt, H. Giessen, and M. Lippitz, "Enhancing the Optical Excitation Efficiency of a Single Self-Assembled Quantum Dot with a Plasmonic Nanoantenna," Nano Lett. 10, 4555-4558 (2010).

[4] J. D. Plumhof, V. Kápek, L. Wang, A. Schliwa, D. Bimberg, A. Rastelli, and O. G. Schmidt, "Experimental investigation and modeling of the fine structure splitting of neutral excitons in strain-free GaAs/AlxGa1-xAs quantum dots," Phys. Rev. B 81, 121309 (R) (2010).

8424-44, Session 9

Surface plasmon polaritons excitation by second-harmonic generation in inorganic crystaline nanowires deposited on thin metal films

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With the recent rapid development within the field of plasmonics, the need for practical and efficient local sources for exciting surface plasmons has increased. The classic prism based excitation schemes are impractical for most applications and alternative methods based on e.g. quantum dot luminescence are non-coherent and have limited tunability. We here present an alternative approach based on second-harmonic generation (SHG) in inorganic crystalline nanowires, which we will show can be used as a coherent tunable local source for surface plasmon polariton (SPP) excitation. Inorganic crystalline nanowires made of e.g. zinc oxide or potassium niobate (KNbO3) have previously been shown to have a large second-order optical non-linearities, which allows for efficient second-harmonic- and sum-frequency generation. It has also been demonstrated that the fields generated by scattering off nanofibers deposited on an air/metal interface can couple to SPP modes in the interface and thereby excite SPPs at the interface. We have combined SHG in nanofibers with SPP excitation through scattering off nanofibers. More specifically, we have used KNbO3 nanowires deposited on thin silver and gold surfaces to generate second-harmonic radiation and have demonstrated that this second-harmonic radiation can be efficiently coupled into SPP modes at the air/metal interface. The generated SPPs were detected by angle resolved leakage radiation spectroscopy for a large range of wavelengths and the resulting spectra recorded using silver and gold interfaces respectively have been compared.

8424-45, Session 9

Nanoantenna-enhanced ultrafast nonlinear spectroscopy of a single gold nanoparticle

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Optical nanoantennas, just like their radio-frequency equivalents, enhance the light-matter interaction in their feed gap. Antenna enhancement of small signals promises to open a new regime in linear and nonlinear spectroscopy on the nanoscale. Without antennas especially the ultrafast nonlinear spectroscopy of a single nanoobject is very demanding. We present the first antenna-enhanced ultrafast nonlinear optical spectroscopy [1]. In particular, we utilize a disc-shaped dipole antenna (diameter 75 nm) to determine the nonlinear transient absorption signal of a single gold nanoparticle (diameter 40 nm). The transient response is caused by mechanical breathing oscillations, reflection the elastic properties on the nanoscale. We trigger the mechanical oscillations of nanoparticle and antenna by impulsive heating through a pump pulse (800 nm). After a variable time delay a probe pulse (530 nm - 750 nm) interrogates the transient absorption of both particles. Due to their different mechanical oscillation frequencies, we can separate the two responses.

In our current setup, a single 40nm particle is at the limit of our detection capabilities. Using the optical nanoantenna,. we increase the signal amplitude by an order of magnitude which is in good agreement with our analytical and numerical models. We expect to be able to study the mechanical properties of structures with dimensions below 10 nm, where classical continuum mechanics is no longer applicable. Beyond that, our method will find applications in linear and nonlinear spectroscopy of nanoobjects, ranging from single protein binding events via nonlinear tensor elements to the limits of continuum mechanics.

[1] T. Schumacher et al., Nat. Comms., 2, 333 (2011)

8424-46, Session 10

Surface plasmon detectors on silicon

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Surface plasmon-polariton (SPP) detectors, or SPP-enhanced detectors, combine a metallic nanostructure that supports SPPs with a semiconductor detector structure such as a Schottky or a pn junction. Involvement of SPPs in the detection process confers characteristics such as enhanced absorptance and spectral selectivity to the detector. Such characteristics can be exploited to advantage in applications. One application of strong current interest is the detection of sub-bandgap radiation in silicon, particularly at telecommunication wavelengths (1310 and 1550 nm), for low-cost optical communications. Internal photoemission on metal-silicon Schottky contacts is a broadband detection mechanism (optical and electrical) suitable for the detection of sub-bandgap radiation but it is inherently inefficient. However Schottky contacts can be structured such that SPPs are excited thereon, resulting in a significant enhancement of the absorptance and responsivity of the detector. Several structures that exploit SPPs to enhance photodetection are discussed and reviewed. Structures capable of high-speed operation (> 10 Gbits/s) at 1310 and 1550 nm in silicon are presented.

8424-47, Session 10

Surface plasmon polariton waveguiding and emission by organic nanofibers

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We experimentally demonstrate the use of organic nanofibers, fabricated by self-assembly of para-Hexaphenylene molecules (p-6P), as defined sources for the excitation of surface plasmon polaritons (SPPs) at a gold-vacuum interface. Furthermore, we show that the nanofibers act as local dielectric distortions at the gold surface that facilitate dielectric-loaded SPP waveguiding. The excitation of SPPs by femtosecond near-infrared light pulses using different coupling techniques is imaged in this work using interferometric time-resolved photoemission electron microscopy (ITR-PEEM). This technique allows us to monitor the SPP propagation with attosecond accuracy and subwavelength spatial resolution.

The experimental results are quantitatively reproduced by analytic simulations utilizing Huygens principle. This allows us to recover the the polarization field associated with the SPP as well as propagation parameters such as group velocity and damping of the SPP modes. The flexibility and tuneability of phenylene-based nanofibers in their morphology and intrinsic optical properties opens up future applications to fabricate custom-designed nanoscale SPP's devices.

8424-48, Session 10

Hybrid silicon-plasmonics: efficient waveguide interfacing for low-loss integrated switching components

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Recently, the interfacing of planar plasmonic and silicon-on-insulator (SOI) waveguides has attracted significant research interest. Efficient coupling between such waveguides enables the collaboration of the two most prominent technologies for nanophotonics, i.e., plasmonics

and silicon photonics, paving the way for hybrid silicon-plasmonic circuits that can benefit from the distinct advantages of each platform. Specifically, these include the low propagation losses of SOI waveguides and the low power consumption of tunable plasmonic components, stemming from field enhancement at metal/dielectric interfaces.

We present a thorough numerical investigation of end-fire coupling between dielectric-loaded surface plasmon polariton (DLSPP) and compact SOI waveguides. Simulations are based on the three-dimensional vector finite element method (3D-VFEM). The interface geometrical parameters leading to optimum performance, i.e., maximum coupling efficiency or, equivalently, minimum insertion loss (IL), are identified. We show that coupling efficiencies as high as 85 % are possible. In addition, we quantify the fabrication tolerances about the optimum parameter values, in order to account for possible misalignments in fabrication as well as resolution limitations. To the same end, we assess the effect of a metallic stripe gap on insertion loss.

Practical integrated components that can profit from the low-loss coupling between these two platforms are longitudinal DLSPP 2x2 switches. All-plasmonic devices based on Mach-Zehnder Interferometer (MZI) or Dual-Mode Interference (DMI) arrangements have been already proposed. In both cases, increased ILs have been identified as the bottleneck of their performance. For the purpose of reducing IL, the passive input-output sections of these switches, i.e., the 3dB-couplers and Y-junctions for the MZI and DMI configurations, respectively, can be replaced by low-loss SOI-waveguide counterparts. We numerically demonstrate through FEM-based vectorial beam propagation method (BPM) simulations that hybrid silicon-plasmonic 2x2 switches can significantly outperform the all-plasmonic ones in terms of IL, while maintaining the high extinction ration (> 25 dB), small footprint and efficient tuning traits of plasmonic technology.

8424-49, Session 10

Diamond nanoparticles as deterministic quantum plasmon launchers

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Using an all-optical scheme, we can reproducibly attach a well-selected single nanodiamond (ND) of ≈ 25 nm in size with single or double nitrogen-vacancy (NV) occupancy onto the apex of optical fiber-tips for near-field scanning optical microscopy (NSOM). This achieves single-ND-based active optical tips. We have implemented such tips in a NSOM environment. Illuminating the grafted ND with a laser light guided by the fiber itself and using only the fluorescence light generated by the ND as nanosource of light achieves a genuine scanning single-photon microscopy [2] that can be run on a long term thanks to the exceptional photostability of the NV [3]. We have further shown that the ND-based active tip efficiently launches SPs into gold films, either homogenous or nanostructured, that are dipped into its optical near field [4]. Since the ND is a quantum source of light, one, or at most two SPs, depending on the actual NV occupancy, forms the experimental images. This is a first successful step towards a “deterministic” quantum plasmonics where single plasmons can be optically launched at any freely chosen position in a plasmonic receptacle.

In this talk, we will first review our grafting protocol and our demonstration, assisted by suitable microscopy (for example leakage radiation microscopy), of quantum SP launching. We will comment on the spatial resolution offered by our single-photon tips [5] and on the wave-particle duality for SPs [6] revealed by our experiments. Then, we will present some prospects to our work in the extension of groundbreaking concepts of quantum optics to the plasmonics world as well as in the plasmonic entanglement of qubits.

[1] A. Gonzalez-Tudela et al, PRL 106, 020501(2011)

[2] A. Cuche et al, Opt. Express 17, 19969 (2009)

[3] R. Brouri et al, Opt. Lett. 25, 1294 (2000)

[4] A. Cuche et al, Nano Lett. 10, 4566 (2010)

8424-50, Session 10

Measurement and reduction of damping in plasmonic nanowires

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Metal nanostructures sustaining surface plasmon (SP) excitations are basic building blocks for nanophotonic systems and show promise for applications in, e.g., optical sensor devices, photovoltaics and data storage. A geometry of particular interest is the nanowire, i.e., a metal structure with sub-wavelength cross-section extending over many wavelengths along the wire axis. The wavelengths of SP modes propagating along a nanowire scale with the cross-section dimension of the wire, thus showing no cut-off behaviour (for the fundamental mode) as for a dielectric waveguide. The SP fields are highly confined and the correspondingly high mode densities give rise to efficient coupling with photon emitters. Plasmonic nanowires have been thoroughly investigated in recent studies reporting on SP propagation, the coupling of SPs with light and the interaction with single photon emitters as quantum dots or color centers in nanodiamonds. Furthermore, plasmonic nanowires provide an appealing platform for photonic logic circuits, detectors and transistor functionality.

We report on a spectroscopic study of the damping of plasmonic modes in silver and gold nanowires. Based on scattered light spectroscopy on single- and polycrystalline wires we deduce quantitatively the relative damping contributions due to metal crystallinity and the type of the supporting substrate, optically absorbing or non-absorbing. Furthermore, we show that despite their relatively strong damping lithographically fabricated polycrystalline nanowires can be applied for plasmonic waveguide networks, which considerably widens the range of potential nanowire applications.

8424-51, Session 11

Near-field microscopy using localized molecular second harmonic generation at a metallic tip

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In 2000, a new concept was introduced [1] aiming at improving the resolution in scaning near field optical microscopy (SNOM). This so called “active tip” concept, relies on the realisation of a point like secondary light source at a SNOM tip. Very interesting results mainly focussed on the development and anchoring of highly luminescent nanoobjects to SNOM tips could be demonstrated [2,3].

Since it is not limited by photodegradation or quenching effects, Second Harmonic Generation (SHG) appears as a valuable alternative. In the case of dipolar approximation however, the existence of a noncentrosymmetry is mandatory to get a non-vanishing signal. We have recently proposed an original technique taking into profit local SHG effects in a molecular solution [4]. We have shown that the static electric field present inside a scanning tunneling microscope (STM) junction can be used towards creating a very local noncentrosymmetry via molecular orientation under the tip [4]. A experimental set-up was specifically designed consisting in the integration of a STM head to an inverted optical microscope, coupled to a femtosecond Ti-Saph laser excitation. The operation of this system has enabled to get the first images with a SHG contrast of a sample structured at the micron scale [5].

As we will discuss it during the presentation, the objective is now to improve resolu-tion. To this respect, electromagnetic field engineering appears as a key point. One way consists in exploiting optical nano-antenna effects. In a first approach, we have recently demonstrated the possibility to benefit from local electromagnetic field enhancement effects occurring in the presence of metallic nano-wires [6]. Extrapolation of these results shows that imaging with about 50 nm resolution should be within reach, which opens new perspectives in the field of optical local probe microscopy.

[1] J. Michaelis et al., Nature, 405, 325 (2000).

[2] A. Drezet, A. Cuche, S. Huant, Optics Comm., 284, 1444-1450, (2011) and references therein.

[3] A. Hartschuh, (2008), Angew. Chem. Int. Ed. 47, 8178 - 8191 and references therein.

[4] I. Berline, C. Fiorini-Debuisschert, C. Royal, L. Douillard, F. Charra, J. Appl. Phys.,104,103113, (2008).

[5] I. Berline, L. Douillard, F. Charra, C. Fiorini-Debuisschert, Controlling molecular organization at the nanoscale for localized second harmonic generation, proceedings SPIE (Nanophotonics III, Bruxelles, 2010)

[6] I. Berline, PhD thesis, ENS Cachan, October 19th, 2010. Article in preparation

8424-52, Session 11

Imaging of DNA liquid-crystalline phases by polarization sensitive two-photon fluorescence microscopy

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The studies of the mechanism of self organization of DNA chains into liquid crystalline phases as a biomimetic model of DNA packing in the cell nuclei are of great interest [1, 2]. This contribution reports on the investigation of the structure of DNA pre-cholesteric, cholesteric and columnar phases by means of polarization optical microscopy (POM) and polarization sensitive two-photon microscopy (PSTPM). PSTPM was successfully introduced by our group to resolve the 3D structure of ordered DNA stained with fluorescent dyes as well as to establish the relative orientation of the dye transition dipole with respect to the long axis of the DNA helix [3, 4]. We are also exploring the doping of DNA in similar structures with luminescent plasmonic nanorods to trace their organization in the DNA matrix and to observe the mutual impact of the nanostructures on the LC phases of DNA and the LC structures onto ordering of the nanorods.

The organization of liquid crystal phases formed in aqueous solutions of DNA depends on the properties of the solution (e.g. DNA concentration) and dopant molecules (i.e binding mode, charge) [5]. We discuss this influence basing on one- and two-photon polarized light microscopy and local ellipsometric analysis of the two-photon fluorescence emission. Interpretation of the results is performed using a theoretical model developed for PSTPM investigation of isolated nanoparticles [6]. We comment on the scope and limitations of the technique and on the optimization of measurement conditions towards specific DNA samples.

References

[1] Leforestier A and Livolant F, Biophys. J. 65, 56 (1993).

[2] Livolant F, Levelut A M, Doucet J and Benoit J P, Nature 339, 724 (1989).

[3] Mojzisova H., Olesiak J, Zielinski M, Matczyszyn K, Chauvat D and Zyss J, Biophys. J. 97, 2348 (2009).

[4] Olesiak J, Matczyszyn K, Mojzisova H, Zielinski M, Chauvat D and Zyss J, Mat.Sci.-Poland 27, 813 (2009).

[5] Olesiak-Banska J, Mojzisova H, Chauvat D, Zielinski M, Matczyszyn K, Tauc P, Zyss J, Biopolymers 95, 365 (2011).

[6] Cherstvy A. G., J. Phys. Chem. B 112, 12585 (2008).

[7] Zielinski M., Winter S., Kolkowski R., Nogues C., Oron D., Zyss J., Chauvat D. Optics Express 19: 6657 (2011)

8424-53, Session 11

Imaging of waveguided and scattered interferences in individual GaAs nanowires via second-harmonic generation

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Semiconductor nanowires (NWs) are widely studied for their potential applications in optoelectronics. With their unique material properties they are considered as key building blocks for future photonics devices. Despite the recent advances in the fabrication of GaAs NWs structures and the material characterization, many optical mechanisms are still to be explored at the nanoscale for future applications, i.e. lasers. Nonlinear optical properties are particularly interesting for realizing coherent optical sources in several spectral regions. Second-harmonic generation (SHG) and other nonlinear wave mixing processes can convert infrared light into visible light and open up a wide variety of applications in different spectral ranges. SHG has been measured in non centrosymmetric semiconductor crystal nanostructures as GaN, ZnO or GaAs. However, the tightly focused point by point optical scanning methods usually used to illuminate the samples, e. g. scanning confocal or near field microscopy, do not allow for investigating waveguiding and interference effects in such subwavelength anisotropic nanostructures. Therefore, we use a wide illumination area for the near infrared incident wavelength from a homemade transmission microscope and observe SHG interference patterns in single GaAs NWs grown via the Au-assisted vapor-liquid-solid (VLS) mechanism on (111)B GaAs wafers.

The NWs are manually transferred by pressing the growth substrate on glass substrates covered with a chromium conductive layer for scanning electron microscopy (SEM), which contains transparent windows for optical transmission measurements. A pulsed laser beam originated from a Ti:Sapphire oscillator is slightly focused with a 50-mm lens down to a focal spot with a diameter of 33 µm. The incident wavelength is centered at 820 nm and the pulse duration at the sample position is about 280 fs at 80 MHz repetition rate and 45 mW average power. All measurements are done at room temperature. We use a narrow band pass filter centered at 410 nm and color filters in front of the cooled electron-multiplied charge coupled device (EMCCD) to block the near infrared pump light and collect only the visible SHG signal.

A distinct periodic pattern is recorded at the SHG wavelength of 410 nm suggesting a phenomenon related to optical cavity interferences supported by the GaAs NW. Along the 5.7 µm long untapered NW, 9 maxima of the SHG signal can be clearly distinguished in the center of the wire. The periodicity of the modes matches with the effective wavelength of a guided mode in GaAs NW with a radius of 78 nm, which is confirmed by SEM and atomic force microscopy (AFM). We propose a model to explain the 2pi periodicity of the interference pattern using waveguiding and Mie scattering theories. For tapered NWs, we demonstrate that modes propagate down to 75 nm radius and vanish at lower width. Finally, our measurements consolidate the use of GaAs NWs grown via the Au-assisted VLS mechanism as an active material for near infrared lasing operation and even in the visible range as optical frequency converter.

8424-54, Session 11

Near-field imaging of surface plasmon resonances in gold nanobars with hollow-pyramid probes

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Scanning Near-Field Optical Microscopy (SNOM) is a powerful technique for diffraction-unlimited optical imaging. By positioning a probe in the near-field of a sample, this method allows mapping of localized electromagnetic fields which are not accessible to far-field techniques. However, the invasive character of such a measurement can lead to a significant influence of the probe, which should be studied carefully for a particular type of probe and setup configuration.

In the presented work, we use a commercial SNOM system (WITec, Germany) with Al coated hollow SiO2 pyramid probes to image surface plasmon resonances (SPRs) in gold nanobars at visible and near-infrared frequencies. The hollow pyramid probes are mechanically robust, offer a good optical resolution (~60 nm), easy polarization control and a broad accessible wavelength range. Although propagating surface plasmon polaritons have extensively been studied with these probes [1], confined SPR modes have received far less attention. The functionality of many nanoplasmonic applications (e.g. bio- and chemical sensing, plasmonic lasing), nevertheless, depend on the specific spatial distribution of the enhanced near-fields associated with the SPR modes in metallic nanoparticles.

Our SNOM results are compared with far-field extinction spectroscopy measurements and FDTD simulations. The near-field maps present similar characteristic patterns as the ones observed in the simulations and literature data obtained using other probe types and techniques [2, 3, 4]. However, the simulations indicate that the geometry of the hollow pyramid probe induces a non-trivial correlation between the near-field maps and the SPRs. Interestingly, we observe a similar excitation strength of even and odd modes in the bars, the first being symmetry forbidden for normal incident plane wave excitation.

Despite the complex probe-sample interaction, our initial results reveal the potential of hollow pyramid probes in near-field studies of confined plasmon modes in metallic nanostructures [5].

[1] R. Zia, et al., Nature Nanotechnology 2, 426 (2007)

[2] K. Imura, et al., J.Chem.Phys 122, 154701 (2005)

[3] J. Dorfmüller, et al., Nano Letters 9, 2372 (2009)

[4] V. K. Valev, et al., PRL 106, 226803 (2011)

[5] N. Verellen, et al., Nano Letters 9, 1663 (2009)

In the presented work, we use a commercial SNOM system (WITec, Germany) with Al coated hollow SiO2 pyramid probes and demonstrate the successful imaging of localized surface plasmon resonances (LSPRs) in gold nanobars at visible and near-infrared frequencies. The hollow pyramid probes are mechanically robust, offer a good optical resolution (~60 nm), easy polarization control and a broad accessible wavelength range. Although propagating surface plasmon modes have extensively been studied with these probes [1], LSPRs have received far less attention. The functionality of many nanoplasmonic applications (e.g. bio- and chemical sensing, plasmonic lasing), nevertheless, depend on the specific spatial distribution of the enhanced near-fields associated with the LSPR modes in metallic nanoparticles.

Our SNOM results are supported by far-field extinction spectroscopy measurements and FDTD simulations. The observed near-field patterns are in good agreement with the simulations and literature data, obtained using other probe types and techniques [2, 3, 4]. Interestingly, we observe a similar excitation strength of even and odd modes in the bars, the first being symmetry forbidden for normal incident plane wave excitation. Compared to the far-field spectra, the modes in the near-field measurements are red-shifted. Simulations indicate that this shift can be attributed to the non-conductive sample-probe interaction.

The successful use of hollow pyramid probes for imaging of LSPRs in gold nanobars motivates further use of these probes for consequent studies of more complex nanostructures and effects [5].

[1] R. Zia, et al., Nature Nanotechnology 2, 426 (2007)

[2] K. Imura, et al., J.Chem.Phys, 122, 154701 (2005)

[3] J. Dorfmüller, et al., Nano Letters, Vol9, No6, 2372 (2009)

[4] V. K. Valev, et al., PRL 106, 226803 (2011)

[5] N. Verellen, et al., Nano Letters, Vol9, No4, 1663 (2009)

8424-55, Session 12

Structure mediated micro-to-nano coupling using spatial light manipulation

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We will outline the specifications of a portable Biophotonics Workstation we recently have developed that utilizes high-speed spatial light modulation to generate an array of currently up to 100 reconfigurable laser-traps making 3D real-time optical manipulation of advanced structures possible with the use of joysticks or gaming devices. The fabrication of microstructures with nanometer-sized features, for example a nano-needle, coupled with the real-time user-interactive optical control allows a user to robotically actuate appended nanostructures depending on their intended function. These micro-platforms carrying nanotools are seen to have potential uses in a variety of micro-biological experiments. Optically actuated nanoneedles may be functionalized or directly used to perforate targeted cells at specific locations or force the complete separation of dividing cells, among other functions that can be very useful for the group of microbiologists.

8424-56, Session 12

Optical trapping and binding in evanescent fields

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Arrays of submicron particles are formed in the evanescent fields created by the total internal reflection of two counterpropagating laser beams. We present experimental observations for arrays of dielectric particles, and show that different array structures can be obtained by varying the wavelength and polarisation of the incident beams. When the evanescent fields are mutually coherent, individual particles can be stably trapped on the nodes or antinodes of the interfering fields, depending on particle size. A particle array formed within interfering evanescent fields can experience both optical trapping and binding forces, often resulting in a variety of modulated structures. Conversely, when the evanescent fields are mutually incoherent and interference fringes are absent, we observe arrays where particle separations are due to optical binding forces alone. We therefore discuss if the observed array structures are due to optical trapping and/or optical binding interactions. Tuning the incident wavelength over a range of λ=840-890 nm and using a number of different particle sizes has allowed experiments to study how the node/antinode affinity of individual particles affects overall array structure [Ref: J.M.Taylor, L.Y.Wong, C.D.Bain, and G.D.Love, “Emergent properties in optically bound matter,” Optics Express, 16(10), 6921-6929 (2008).]

8424-57, Session 12

Slow Bloch mode nanotweezer

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Photonic crystals (PC) have proved their ability to shape the electromagnetic field. In particular, it has been shown that their resonances could give rise to huge field enhancement. This is done usually by creating a defect (microcavity) within the band gap. It has been shown that such cavity could be very efficient for trapping single nanoparticle.

We will present in this paper an alternative approach: instead of relying on defect within the photonic bandgap, we will use the PC ability to generate slow Bloch mode. Because of the low group velocity, an important field enhancement is expected. Moreover, we used a mode above the light line which allows an efficient addressing from free space. We will thus expect efficient optical trapping with a low excitation power.

We will first present the FDTD modeling of the slow Bloch mode structure and shows that a field enhancement of many thousands could be easily obtained. We will also show that this structure could be easily and efficiently excited using a wide (6µm) Gaussian beam. The resulting mode presents a periodic modulation that is suitable for collective trapping of nanoparticles.

The second part will be devoted to the experimental demonstration of the trapping capability of such structure. We will show that 250 nm radius latex beads are trapped using less than 1mW laser power.

8424-58, Session 12

Measuring air viscosity by optically rotating trapped birefringent microparticles

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Due to conservation of angular momentum birefringent particles experience a torque when illuminated by circular polarized light. This effect can be used to controllably rotate microparticles. Together with optically trapping, it is possible to create a small turbine whose rotation rate is dictated by the balance between the optical torques and the rotational Stokes drag. By recording the change in polarization of the incident trapping beam and the terminal rotation velocity, we can measure the viscosity of the gas around the rotating micro-particle. Interestingly, trapping and rotating particles in air is intrinsically linked to the aberrations present in the optical system. Indeed, the high refractive index change at the air-glass interface induces large spherical aberrations of the beam and at the same time produces a large “scattering force” acting on the microparticle. Here, we present the experimental implementation of a setup rotating vaterite microparticles in air and the numerical simulations showing the contributions of the spherical aberrations and beam profile on the stable trapping and terminal velocity.

8424-59, Session 12

Holographic optical bottle beams

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Optical tweezers have introduced enormous improvements for the manipulation of transparent dielectric particles in various implementations. The manipulation of absorbing matter, however, is typically handicapped by strong scattering forces that cannot be counterbalanced by gradient forces. To overcome this shortcoming, light fields with a hollow intensity distribution, so called optical bottle beams, have been proposed recently [1]. In these light fields, scattering forces are minimized and absorbing matter is repelled from regions of high light intensity by the photophoretic force. This force, which originates from optically induced thermal gradients on the particle’s surface, is orders of magnitude stronger than typical forces in optical tweezers, strong enough to stably trap matter in air.

In this contribution, we present for the first time complex holographic optical bottle beams that are capable of trapping multiple absorbing particles, such as carbon nanotubes (CNTs) or buckminster fullerenes, simultaneously and manipulate them independently in all three dimensions. Our new approach combines well-established techniques for the generation of multiple point traps in optical tweezers [2] with recently proposed hollow intensity distributions by means of holographic techniques [3]. It consists of the multiplication of the output of a prism-and-lenses algorithm with a predefined bottle beam hologram and is therefore computationally efficient. The desired three-dimensional bottle beam field is generated as the Fourier transform of this calculated hologram. Hence, our approach can be mathematically described as a convolution of the bottle beam configuration with a point array of designated trapping positions. In contrast to previous methods for the generation of optical bottle beams the proposed approach improves the diffraction efficiency, which enables higher numbers of traps at typically available laser power. As the manipulation of beams is accomplished by a programmable phase-only spatial light modulator, our approach is capable of moving trapped matter along predefined, arbitrary paths without the need for mechanical scanning, just by the adjustment of our phase hologram. To verify the precise manipulation capabilities, trapped particles are tracked in all three dimensions simultaneously by two complementary microscopes, covering the xz and xy planes, respectively. Furthermore, it is self-evident that the presented convolution approach is not limited to bottle beams but can be easily expanded to generate an array of arbitrary holographic field distributions.|

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References:

[1] P. Zhang, Z. Zhang, J. Prakash, S. Huang, D. Hernandez, M. Salazar, D. N. Christodoulides, and Z. Chen, Opt. Lett. 36, 1491(2011).|

[2] M. Woerdemann, C. Alpmann, and C.Denz, Appl. Phys. Lett. 98, 111101 (2011).|

[3] C. Alpmann, M. Esseling, P. Rose, and C. Denz, sub. to Appl. Phys. Lett. (2011).

8424-60, Session 12

A balanced, phase sensitive back-focal plane interferometry technique to determine dynamics of a trapped bead in optical tweezers

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Back-focal plane interferometry is typically used to determine displacements of a trapped bead which lead to trapping force measurements in optical tweezers. In most cases, intensity shifts of the back-scattered interference pattern due to bead displacement are measured by a position sensitive detector placed in the microscope back-focal plane. However, in intensity-based measurements, the axial displacement resolution is typically worse than the lateral resolution since for axial displacements, the inherent resolution of the position detector cannot be used. In this paper, we demonstrate that measurement of the phase of the back-scattered light yields high axial displacement resolution, and can also be used for lateral displacement measurement.

Our trapping chamber consists of a standard glass coverslip and a microscope slide separated by a spacer with the sample consisting of monodispersed polystyrene beads (diameter 1 or 3 um) in aqueous solution. A single mode diode laser at 1064 nm is used for trapping, while a stabilized single mode tunable diode laser at 780 nm is used for detection. In our experiments, we trap the bead close to the microscope slide. The light at the microscope back-focal plane consists of back-scattered light (at 780 nm) from the bead and unscattered light from different regions of the sample chamber. We separate out the scattered and unscattered components by a confocal arrangement consisting of a spatial filter used in combination with two apertures. Due to the confocal arrangement, and the fact that we trap the bead close to the top slide, we can ensure that most of the unscattered light is that reflected from the slide. We proceed to beat the two separated components in a Mach-Zender interferometer where we use balanced detection to improve our fringe contrast, and thus the sensitivity of the phase measurement. The phase of the output signal from the interferometer changes when the bead moves with respect to the top slide, with a 2pi phase change

for axial bead displacement of a unit wavelength of the detection laser. However, due to the curvature of the bead, there would be a phase change for lateral motion also which we calibrate by moving the trapped bead controllably using an acousto-optic deflector. For the lateral motion, we match experimental results with a theoretical simulation to find the shift of the overall phase contour of the back-scattered light by using plane wave decomposition in conjunction with Mie scattering theory, where we consider a superposition of the phase of the scattered light from the trapped bead and that from the slide. We obtain an agreement to within 10% between experimental and simulation results.

In addition, our technique is able to track the Brownian motion of trapped beads from the phase jitter so that, similar to intensity-based measurements, we can also use it to determine the spring constant of the trap, and thus the trapping force. The sensitivity of our technique is limited by path drifts of the external interferometer. By locking the interferometer to a frequency stabilized diode laser, we can presently obtain displacement measurement resolution of around ~2 nm, which could be improved in future.

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8425-01, Session 1

Enhancement of nonlinear effects in slow light photonic crystal waveguides and its application to all-optical signal processing and quantum integrated optics

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Slow light propagation in photonic crystal waveguides has been shown to substantially enhance the efficiency of nonlinear processes, making this platform promising for realizing nonlinear devices with low power consumption and short length scale. In addition, the possibility of engineering the dispersion in these structures makes it possible to achieve nonlinear functions that can operate at high-bit-rates. Recent demonstrations do not only include nonlinear processes experienced by a single probe, but also more complex schemes where several waves at different frequencies are involved, such as in four-wave mixing and third-harmonic generation, which truly open the way to all-optical signal processing on-chip.

While a lot of these demonstrations have made use of silicon, this material suffers from high two-photon absorption in the near-infrared and the resulting creation of absorbing free carriers. Because these detrimental nonlinear processes are also enhanced by slow light, they strongly limit the benefit of slow light photonic crystals for some applications.

Here, we will first present how slow light dispersion engineered photonic crystal waveguides can be efficiently exploited for all-optical signal processing, using four-wave mixing or third-harmonic generation for achieving optical performance monitoring and demultiplexing in ultra-compact waveguides and at high-bit rates. We will then show how slow light structures made of a nonlinear material with reduced nonlinear loss, such as chalcogenide glass, can be successfully combined with slow light, so as to provide improved efficiency and expand the number of applications with respect to silicon. Lastly, we will present recent results demonstrating that slow light enhanced nonlinearities in photonic crystal waveguides could also be used to generate correlated pairs of photons from spontaneous four-wave mixing in very short (<100 m) structures, which is of high interest for quantum applications.

8425-02, Session 1

Slow light propagation in photonic crystal slab waveguides: theory and practical issues

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Photonic Crystals may play an important role in future integrated optical components by providing new means for manipulating light at the subwavelength scale. In this paper, we consider the propagation of slow light optical pulses inside photonic crystal slab waveguides (PCSW) both from a theoretical and an application point-of-view. The numerical model used relies on a nonlinear envelope propagation equation that includes the effects of second and third order dispersion, optical losses and self phase modulation. The coefficients of the propagation equation are determined by the mode parameters calculated by our implementation of a plane wave expansion (PWE) mode solver based on the conjugate gradient minimization of the Rayleigh-Ritz quotient. Photonic crystal waveguides formed in rectangular and triangular lattices are examined for a variety of line defects. The mode solver fully accounts for the 3D nature of the structures. Using a least sense polynomial fitting on the defect mode dispersion relation curve, we are able to estimate the dispersion parameters highlighting the restrictions of the light line. Pulse propagation is examined both in the linear and nonlinear regime. It is numerically shown that for rates of 10Gb/s and 40Gb/s, nanosecond delays can be achieved through the PCSW defect modes without excessive pulse broadening in both regimes, implying a buffering capacity of 10bits or more depending on the bit rate and the length of the waveguide. In the nonlinear case, it is shown that soliton pulses exhibit less broadening than pulses in the linear case. In comparing the linear and the non-linear case we consider launching pulses with the same initial full width at half maximum or the same RMS width. We also show that the optical power necessary to maintain soliton propagation ranges in the milliwatt power level. The influence of optical losses on the soliton pulse broadening factor is also incorporated and discussed providing a more practical perspective. The results demonstrate the potential of implementing a variety of linear and nonlinear signal processing applications in PCSWs, such as optical buffering.

8425-03, Session 1

Slow light in slot photonic crystal waveguides by dispersion engineering

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The strong reduction of the group velocity in photonic crystals allows investigation of light-matter interactions and all-optical signal processing [1-2] by dramatically increasing the local electromagnetic energy density, whereas benefits from non linear materials are gained by the introduction of a slot which confines light in the low index material [3]. Therefore, Slot Photonic Crystal Waveguides (SPCW) ensure the combination of slow light and strong confinement within the slot [4]. Nevertheless, such devices are limited by difficulties to fill narrow slots and requirements of a flat band slow light.

Our work addresses these issues by proposing a novel design of wide SPCW filled by a polymer, where we introduce corrugations to the slot. This allows a group index bandwidth product of 0.12, while the hole array is merely left unchanged. We achieved group index above 40 over a 5nm bandwidth.

Eigenmodes are calculated by Plane Wave Expansion method. The detailed method is exposed in Ref. We then analyze the transmission of the structure by Finite Difference Time Domain method and by adapting the mode by strip-to-slot waveguide converter and fast light to slow light regime transition region, we obtain high transmission.

We show that structuring the slot in a SPCW allows performing dispersion engineering in order to achieve very low group velocities over an exploitable bandwidth. This hybrid structure of SPCW offers possibilities to realize devices requiring strong interactions between light and an optically non-linear low index material by providing an ultra-high optical density while easing the filling of the slot due to its width. We will present the methodology of the dispersion engineering and transmission results. We will investigate the losses and the non linear properties by FDTD analysis, and provide our last experimental results.

References

[1] B. Corcoran et al., Opt. Exp. 18 7770 (2010).

[2] T. Baba, Nat. Phot. 2 465 (2008).

[3] V. R. Almeida et al., Opt. Lett. 29 1209 (2004).

[4] A. Di Falco et al., Appl. Phys. Lett. 92 083501 (2008).

[5] C. Caer et al., Photon. Technol. Lett. 23 1298 (2011).

8425-04, Session 1

Slow light propagation due to nonlinear interaction in a 2D semi-conductor photonic crystal cavity

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The phenomenon of slow light (SL) has become a topic of growing interest because it offers another level of control over light-matter interactions and potential applications such as optical buffers or phase shifters. The most efficient techniques are based on nonlinear coherent optical interactions such the coherent population oscillations (CPO) effect [1] or Electromagnetically Induced Transparency (EIT) [2]. SL propagation is also obtained through the engineering of the index of refraction in the photonic crystals [3]. The association of both effects is however still missing.

In this paper, we present our work on SL propagation in a semi-conductor-based photonic crystal cavity (PhCC). We have associated the SL propagation induced by the CPO effect achieved in the absorbing Quantum Wells (QWs) present in the PhCC with the dispersive properties of a nonlinear PhCC. We show that the cavity lifetime is enhanced thanks to the combination of two effects: CPO-based index dispersion and strong dispersion in vicinity of the nonlinear PhCC resonance. The PhCC used is on InP having 4 InGaAsP/InGaAs QWs with an absorption of about 60 cm-1 at 1.57 µm. The CPO effect is achieved using the intensity modulation technique and the laser beam is coupled into the cavity using a tapered optical fibre. Using a homemade locking amplifier we were able to measure the optical delay induced in the PhCC reaching about 600 ps, longer than the storage time in an empty cavity or when the CPO effect is considered on its own. These large delays show that the lifetimes of optical resonators can be enhanced by inclosing strong dispersive materials in the cavities [4]. Details on both experimental investigations and theoretical analysis will be discussed in the presentation.

References:

[1] R.W. Boyd et al., Phys. Rev. A 24, 411 (1981)

[2] S. E. Harris, Phys. Today 50, No. 7, 36 (1997)

[3] T. Baba, Nature photonics 2, 465 (2008)

[4] M. Soljacic et al., Phys. Rev. E 71, 026602 (2005)

8425-05, Session 1

Airy beam induced optical routing

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Photonics research provides the vision to overcome the unavoidable bandwidth constraints of electronics by replacing electrons with photons heading towards an all-optical computing and information processing architecture. When thinking about this reasonable transition, the question of how to implement a switchable all-optical guiding of light arises immediately.

Materials that change their properties due to light whereupon light itself reacts on the changed material environment provide the missing link in order to control light by light itself. Promising examples in this field are photorefractive crystals like strontium barium niobate (SBN). The illumination of such a material with structured low intensity writing-beams yields optically induced photonic structures with fascinating properties regarding the propagation of light.

This so-called optical induction technique has been utilized to demonstrate, for instance, discrete solitons [1], Zener tunneling and Bloch oscillations [2], as well as discrete vortex solitons [3-5]. In addition, the optical induction approach takes advantage of SBN's electro-optic characteristics and therewith facilitates highly adaptive and reconfigurable photonic devices.

Naturally, the intensity distribution of a beam used for the induction of two-dimensional photonic structures should be modulated in the two transverse dimensions but has to remain invariant in the direction of propagation. Light fields fulfilling this requirement are commonly denoted as nondiffracting beams and while in the past only rather simple geometries were studied, the interest currently turns towards more complex patterns in this field [6-8].

In this contribution, we present a new all-optical routing scheme based simultaneously on optically induced photonic structures as well as the fascinating Airy beam familiy. Airy beams are accelerating beams that retain their spatial shape during propagation. Since their first demonstration in 2007 [9], they attracted an enormous scientific interest and have been used to demonstrate for instance abruptly autofocus- ing waves [10], linear light bullets [11], or - in micromanipulation experiments - optical snowblowers [12].

The presented work utilizes these accelerating beams for the implementation of an all-optical routing setup. We present our concept of an Airy beam induced optical router, discuss the scientific background, and introduce the underlying physical system as well as its experimental realization. The demonstrated results show an all-optical router with as many as 16 individually addressable output channels. In addition, we are able to activate multiple channels at the same time providing us with an optically induced splitter with configurable outputs as well. We are convinced that this new approach for all-optical routing can be realized in multiple physical systems and will find many significant applications.

References:

[1] J.W. Fleischer et al., Nature 422, 147 (2003).

[2] H. Trompeter et al., Phys. Rev. Lett. 96, 053903 (2006).

[3] D.N. Neshev et al., Phys. Rev. Lett. 92, 123903 (2004).

[4] J.W. Fleischer et al., Phys. Rev. Lett. 92, 123904 (2004).

[5] B. Terhalle et al., Phys. Rev. Lett. 101, 013903 (2008).

[6] J. Xavier et al., Adv. Mat. 22, 356 (2010).

[7] M. Boguslawski et al., Phys. Rev. A 84, 013832 (2011).

[8] J. Becker et al., Opt. Express 19, 9848 (2011).

[9] G.A. Siviloglou et al., Phys. Rev. Lett. 99, 213901 (2007).

[10] N.K. Efremidis and D.N. Christodoulides, Opt. Lett. 35, 4045 (2010).

[11] D. Abdollahpour et al., Phys. Rev. Lett. 105, 253901 (2010).

[12] J. Baumgartl et al., Nature Photon. 2, 675 (2008).

8425-06, Session 2

Slotted photonic crystals for biosensing applications

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We present a small optical, label-free biosensor based on slotted photonic crystals [1]. This device combines the slot waveguide concept [2], whereby light is guided in a narrow air slot, with photonic crystals in which cavities [3] and slow light behaviour [4] can be engineered. We use cavities based upon the heterostructure approach, demonstrating experimental quality factors of up to 50,000 in air and 4,000 in water [3]. As the peak of the cavity mode interacts with the content of the slot, small changes in refractive index can be inferred from the cavity resonant wavelength with high sensitivity (~500nm/RIU). We also integrate microfluidic channels, which when combined with the small footprint of each sensor, allows for dense multiplexing with only micro-litres of analyte. To enable high performance of the device both the interface and propagation losses must be addressed. As the dispersive properties of the fundamental mode of a standard and slotted photonic crystal differ greatly, a suitable interface for coupling into the device must be found. We utilise a resonant defect approach [5] which preferentially couples into the slot mode. Initial measurements of the propagation losses using the cut-back method suggest that the losses of the slot can be similar to that of a standard channel waveguide for a given geometry. Through careful design we can therefore maximise the amount of light interacting with the sample within a small volume. Functionalising the surface of the device with antibodies allows us to detect specific binding of a target protein on the sensor surface. As a proof of principle demonstration we show detection of dissolved avidin concentrations as low as 15nM using biotin functionalised devices [6]. As many antibodies can be readily conjugated with biotin, this has potential to be used in a variety of biosensing applications.

References

[1] A. Di Falco, L. O'Faolain and T.F. Krauss, Phot. Nan. Fun. Appl. 6, 38-41, (2008).

[2] V.R. Almeida, Q. Xu, C.A. Barrios and M. Lipson, Opt. Lett. 29, 1209-1211, (2004).

[3] A. Di Falco, L. O'Faolain and T.F. Krauss, Appl. Phys. Lett. 94, 063503, (2009).

[4] A. Di Falco, L. O'Faolain and T.F. Krauss, App. Phys. Lett. 92, 083501, (2008).

[5] M.G. Scullion, T.F. Krauss and A. Di Falco, IEEE J. Photonics 3, 203-208, (2011).

[6] M.G. Scullion, A. Di Falco and T.F. Krauss, Biosens. Bioelect. 27, 101-105 (2011).

8425-07, Session 2

Luminescent photonic crystal cavities for fiber optic sensors, coupled dissimilar cavities, and optofluidics

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Photonic crystal (PhC) cavities made in broadband luminescent material offer attractive possibilities for flexible active devices, exploiting the internal light sources. The luminescence enables the cavity to operate as an autonomous entity, independent of an optical access circuit on the host chip. New applications of this property are demonstrated for cavities made in the InGaAsP underetched semiconductor membrane with embedded InAs Quantum Dots that emit in the range of 1400-1600 nm.

Planar photonic crystal nanocavities, were suspended in the membrane by breakable tethers, and released after fabrication by mechanical micromanipulation with a tapered fiber tip. The released cavity particle could be bonded on an arbitrary surface, supposedly by van der Waals forces, with either its face parallel or perpendicular to the receiving surface. A novel fiber-optic sensor with a PhC cavity chiplet attached to the tip of a standard single-mode optical fiber was demonstrated.

A photonic crystal nanocavity, consisting of only three missing neighboring holes, is coupled to a large multimode 60 missing holes cavity. The coupling was studied by the local photothermal tuning of the emission of the small cavity over about three Free Spectral Ranges of the large cavity. A single mode from the small cavity is shown to couple simultaneously to at least three cavity modes of the large cavity, as concluded from level anticrossing data when the small cavity was tuned. The observations are excellently reproduced by a model of coupled Fabry-Perot resonators.

Reconfigurable and movable cavities were created by locally varying the infiltration status by liquid oil near a PhC waveguide or defect cavity. Femtoliters amounts of liquid were transported over the surface by the capillary action of a tapered glass fiber tip micromanipulated in contact with the wet surface. Alternatively, liquid was locally removed on a micron scale using a focussed laserspot.

8425-08, Session 2

Plasmonic device using backscattering of light for enhanced gas and vapour sensing

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Based on recent experimental and theoretical results obtained with gold-glass nanocomposite films [1], we propose a plasmonic device which uses the backscattering of light in order to make a highly sensitive gas/vapour sensor. The backscattered reflectance is used as sensing signal since it has been shown that this component of the diffracted light is much more sensitive to a change of refractive index in the surrounding medium than the specular component [2]. In addition, the backscattering of light presents an azimuthal angular dependency which is viewed as an advantage for practical implementation. The device consists of a SiO2 substrate (refractive index: nsub) which acts as the incidence medium and could be simply a glass plate. On the substrate, a second layer is added which possesses a reduced refractive index, such as ndepl=nsub(1-δn), and could be produced, for example, by thermal electric poling [1]. The thickness of this intermediate layer, ddepl, together with δn, are two parameters which can be optimised in order to maximize light transmission into the third sensing layer. The reduced-index layer actually acts as leaky-waveguide. The third layer is composed of metal (gold) nanoparticles embedded in a thin SiO2 film whose thickness is typically around 100 nm. It can be produced by sputtering for example. Through numerical simulations, stacks of periodic 2D square and hexagonal arrays of gold nanoparticles are compared in order to point out the photonic response of the device with respect to the particle arrangement. Moreover, randomness is introduced into these arrays in order to highlight the robustness of the sensing principle with respect to defaults in the particle arrangement which is relevant with respect to fabrication tolerance issues. We study the backscattered reflectance as it changes according to modifications in the dielectric environment of the sensor at the external surface. Device parameters (ddepl, δn, spacing between particles, gold filling fraction, layer thicknesses) and incidence angles will be optimized for those geometries. The plasmonic structures could be fabricated by depositing successive layers of gold particles which are covered by suitable dielectric material.

[1] M. Beresna, P.G. Kazansky, O. Deparis, I.C.S. Carvalho, S. Takahashi, A.V. Zayats, "Poling-assisted fabrication of plasmonic nanocomposite devices in glass", Advanced Materials 22, p.4368 (2010).

[2] O. Deparis, M. Beresna, C. Vandenbem and P.G. Kazansky, "Light coupling and enhanced backscattering in layered plasmonic nanocomposites", Opt. Express 19, p.1335 (2011).

8425-09, Session 2

Resonant detectivity enhancement of quantum well infrared photodetectors by photonic crystal slabs

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We present a photonic crystal slab (PCS) fabricated from a quantum well infrared photodetector (QWIP). The dielectric slab design provides excellent out-of-plane confinement of photons in the slab wave guide, hereby exhibits much lower losses compared to a plasmonic wave guide. By using a QWIP with a 100x lower absorption than standard we have shown, that the noise due to the dark current can be reduced, while a high responsivity can be maintained due to the high lifetime of photons in the PC resonances [1]. We observed an increase of the maximum operation temperature from around 110K for a standard QWIP up to 200K for a low-doped PCS-QWIP with a peak absorption at λ=8µm. The combined effect of responsivity enhancement and dark current noise reduction results in a 20x enhanced specific detectivity D*.

The thickness of the slab acts as an additional design parameter. For

slabs with a large thickness compared to the photonic crystal lattice constant (slab-to-PC ratio) we have shown, that additional resonance peaks appear in the photocurrent spectrum, which correspond to higher order modes of the slab wave guide [2]. By variation of the slab-to-PC ratio we are able to precisely identify the polarization as well as the order of the slab mode of a resonance by analysis of the resulting peak shift. This method complements the established photonic band structure mapping technique [3] and is applied to characterize a full multi-mode PCS photonic band structure. The measured photonic bands are in good agreement with simulation results of the revised plane wave expansion method (RPWEM) with an effective refractive index approximation.

References:

[1] S. Kalchmair et al., Appl. Phys. Lett. 98, 011105 (2011)

[2] R. Gansch et al., Opt. Express 19, Issue 17, 15990 (2011)

[3] S. Schartner et al., Appl. Phys. Lett. 89, 151107 (2006)

8425-10, Session 3

Cavity quantum electrodynamics in quantum dot and 2D/3D photonic crystal nanocavity coupled systems

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One of the most ultimate goals in the field of the semiconductor lasers is to realize ultra-small lasers consisting of an optical cavity with the size of a wavelength of light and a single (artificial) atom. Since a single atom laser using a single trapped gas atom was demonstrated [1], various efforts have been devoted toward realization of such single emitter laser in solid-state materials. Combination of a single semiconductor quantum dot (QD) [2] with a semiconductor photonic crystal nanocavity is one of the best systems for this purpose. The coupled single-quantum-dot-2D/3D-photonic-crystal-nanocavity system provides with an excellent platform to investigate solid state cavity quantum electro-dynamics (Cavity-QED). In the strong coupling regime, reversible exchange of a single quantum between a single quantum dot and the nanocavity is well-preserved. Though the coexistence of vacuum Rabi oscillation and laser oscillation seems to be contradictory, it has recently been theoretically predicted that the strong-coupling effect could be sustained in laser oscillation [3].

In this presentation, we discuss recent advances in solid state cavity-QED in coupled single-quantum-dot-2D/3D-photonic-crystal-nanocavity systems. First, lasing oscillation in both weak- and strong-coupling regime in a single QD-nanocavity coupled system is demonstrated [4,5]. A high-quality semiconductor optical nanocavity and the strong single QD-field coupling enabled the lasing while maintaining the fragile coherent exchange of quanta. Furthermore, electron-phonon interaction under the cavity-QED conditions shows an asymmetric vacuum Rabi doublet and its temperature dependence, which is a unique phenomenon in solid state semiconductor systems [6].

Fabrication of a three dimensional photonic crystal nanocavity of a high Q-factor (~40,000) embedding quantum dots is also discussed, demonstrating lasing oscillation with systematic reduction of threshold with the increase of the Q-factor [7]. Purcell effect in the three dimensional photonic crystal nanocavity with a single quantum dot is observed with enhanced and suppressed factors of the spontaneous emission rate, respectively [8]. Finally we briefly mention a silicon-based three dimensional photonic crystal nanocavity.

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References

1. J. McKeever, A. Boca, A. D. Boozer, J. R. Buck, and H. J. Kimble, Nature 425, 268 (2003).

2. Y. Arakawa and H. Sakaki: Appl. Phys. Lett., 40, 939 (1982)

3. E. D. Valle, F. P. Laussy, C. Tejedor, Phys. Rev. B 79, 235326 (2009).

4. M. Nomura, N. Kumagai, S. Iwamoto, Y. Ota, and Y. Arakawa, Opt. Express, 17, 15975 (2009).

5. M. Nomura, N. Kumagai, S. Iwamoto, Y. Ota, and Y. Arakawa, Nature Physics 6, 279, (2010).

6. Y. Ota, N. Kumagai, S. Ohkouchi, M. Shirane, M. Nomura, S.Ishida, S. Iwamoto, S. Yorozu and Y. Arakawa, arXiv:0908.0788 (2009)

7. A. Tandaechanurat, S. Ishida, D. Guimard, M. Nomura, S. Iwamoto, and Y. Arakawa, Nature Photonics 5, 91 (2010)

8. A. Tandaechanurat, S. Ishida, D. Guimard, M. Nomura, S. Iwamoto, and Y. Arakawa, unpublished

8425-11, Session 3

Experimental characterization of far-field emission profiles from photonic crystal cavity modes

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Photonic crystal membrane cavities offer an interesting platform for cavity-QED experiments with solid-state emitters. Due to very small mode volume and high quality factor, significantly high Purcell factors can be obtained and, in some cases, the strong-coupling regime can be reached. The out-coupling of light from the membrane plane, however, is typically quite inefficient because, for high-Q cavities, most of the light is emitted at large angles with a highly non-Gaussian spatial profile.

Here we discuss the experimental characterization the spatial far-field profiles for the confined modes of a photonic crystal cavity of the L3 type, finding a good agreement with FDTD simulations. We then link the far-field profiles to relevant features of the cavity mode near-fields, using a simple Fabry-Perot resonator model.

Finally we discuss the design optimization for the case of H1 cavities showing experimentally how the emission profile changes as a function of the size and position of the six holes closest to the cavity center. We find a good compromise between far-field profile and the quality factor, showing that with a reduction of about 20% of the quality factor we can have 90% of the light collected by an objective with numerical aperture 0.8.

These results can be useful for emission engineering from active centers embedded in the cavity and for efficient coupling between spin states of single emitters and light. In particular, the H1 cavity has two orthogonally-polarized modes at degenerate frequencies (in the ideal case, with no fabrication imperfections), which makes it very promising to work in the circular polarization basis, as required by optical spin selection rules for single electrons in self-assembled quantum dots.

8425-12, Session 3

New design for high Q slow Bloch mode cavity

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Small modal volume, high Q cavity has been a major achievement of photonic crystal (PC) structure. This leads to very compact structure such as nanolaser, sensors... Three kinds of approaches have led to these structures:

- The first one uses defect in PC structures that operate below the light line. Here, all the know-how relies on the defect engineering to minimize all the above light line contribution that arises from localization.

- The second uses PC crystal heterostructure operating below the light line. This has led to the highest Q factor ever obtained (such as the results obtained by Noda's team[1]).

- The third approach use slow Bloch mode above the light line. This approach is very interesting since it allows a very efficient resonant coupling using wide vertical Gaussian beam. However, here the Q factor is usely low. Some modifications to a "standard design" is required to improve the Q factor such as a combination with a Bragg mirror or the use of thick layers. All these modification have a technological cost.

The coupling in the first two approaches is often made using guided waves because they operate below the light line. Direct coupling with Gaussian beam is not very efficient.

We present in this work a new approach that combine the advantages of the below and above light line approaches. The structure consists in slow Bloch mode cavity build from the perturbation of below light lines modes. We will shows that the perturbation will allow an easy and direct coupling with a Gaussian beam. The strength of the perturbation allows a deterministic control of the Q factor.

The first part of the presentation will be devoted to 3D FDTD modeling. We will show that it is very easy to get high Q factor using this approach. We will illustrate this approach using a cavity with air modes (modes located in the low index region). Such structures are very interesting for sensing and optical trapping experiment.

The second part will present optical results obtained on real devices. We will report on Q factor of three thousand and that the cavity could be easily addressed with a Gaussian beam.

[1] B.S. Song et al. :Nature materials Vol 4, 207 (2005).

8425-13, Session 3

Efficient free space coupling in 2D semi-conductor photonic crystal nanocavities

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Photonic crystal (PhC) nanocavities have been intensively investigated during the last decade due to their capabilities of achieving tight light confinement and low optical losses simultaneously. Among the different geometries, the cavity proposed by Noda et al. [1], namely a L3 cavity (three holes missing) with shifted end-holes has been widely used in several applications including laser emission and switching devices [2]. However, input/output free space light coupling of such nanocavities is quite challenging. In this regard, near field coupling schemes have been recently developed, such as evanescent coupling using tapered optical fibers. In order to overcome the poor free space coupling, a new cavity design has been recently proposed [3] that totally changes the radiation pattern. This is based on a band folding approach introducing a modulation of the holes size at twice the period of the underlying PhC, which considerably increases the coupling efficiency in the vertical direction [4]. While some measurements of the Q-factor and coupling efficiency were performed, no direct characterization of the far field of such cavities has been performed so far. In this work we have studied different types of L3 photonic crystal cavities and photonic molecules with optimized far field profiles. Radiation patterns from "folded" and "unfolded" cavities were systematically measured and compared. Our PhC cavities are based on suspended InP membranes having four InGaAsP/InGaAs QWs emitting at 1.50 µm. Good agreement between simulations and experimental far field patterns has been found, demonstrating highly directional emission lobes along the sample normal. Furthermore, free space input coupling experiments have been performed showing reflectivity dips of about 30% of contrast with quality factors exceeding 104. These results validate the "folded" L3 cavities as good candidates for small volume and high Q cavities with efficient free space coupling, either in single or coupled cavity configurations.

References:

[1] Y.Akahane, T.Asano, B-S.Song and S.Noda, Nature 425, 944-947 (2003).

[2] M.Brunstein, A.M. Yacomotti, R.Braive, S.Barbay, I.Sagnes, Photonics Journal, IEEE, Vol.2,Issue 4, 642 - 651, (2010).

[3] N-V-Q Tran, S.Combrié, P.Colman, and A. De Rossi, Phys. Rev. B 82, 075120 (2010).

[4] S. L. Portalupi, M. Galli, C. Reardon, T. F. Krauss, L. O'Faolain, L. C. Andreani, and D. Gerace, Optics Express, 16067, Vol. 18, No. 15 (2010).

8425-14, Session 3

Antibonding ground state in photonic crystal molecules

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Following the analogy with quantum mechanics, coupled PCCs are also denominated photonic molecules. With the same approach we call the even (usually nodeless) molecular state a bonding state, while the odd molecular state (which always has a node) is called the antibonding state. Intuitively the molecular ground state is expected to have bonding orbital character and, on the contrary, the first excited molecular state is expected to have antibonding orbital character. Recently it has been shows that the spin orbit coupling can lead to antibonding ground states in quantum dots molecules [1]. Similarly, it has been theoretically predicted that the ground state may change from bonding to antibonding in photonic crystals systems by varying either the distance between the PCCs or their alignment [2, 3].

Here we give a direct experimental proof of the ground state bonding/antibonding nature in coupled PCCs. The challenge is that the parity of the coupled modes refers to a phase property which is quite difficult to be probed.. Recently we have demonstrated that a revisited photonic Young's like experiment, based on photoluminescence (PL), where the slits are replaced by two identical photonic nanocavities with embedded quantum dots (QDs), can directly probe the photonic mode symmetry by simply using far field (FF) photoluminescence analysis [4]. In this contribution we use the revisited Young's type experiment to demonstrate that the ground state in photonic crystals may actually change from bonding to antibonding character depending on the spatial alignment of the two isolated cavities. The effect is interpreted in terms of the photonic energy functional.

[1] M. F. Doty, et al. Phys. Rev. Lett. 102, 047401 (2009)

[2] C.S. Kee, et al. Phys. Rev. B 67, 073103 (2003)

[3] A. R. A. Chalcraft, et al., Opt. Express 19, 5670 (2011).

[4] F. Intonfi et al. PRL 106, 143901 (2011).

8425-15, Session 4

Enhanced light-matter interaction of extended quantum dots in photonic nanostructures

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The efficient enhancement of the interaction between light and matter is the essential requirement for solid-state quantum photonics experiments. Either photonic or electronic degrees of freedoms can be engineered. We review recent experiments demonstrating that photonic nanstructures such as photonic crystals can be used for that purpose, and explain how the extended nature of quantum dots can be used as an additional resource to enhance the interaction even further. In particular we demonstrate that the celebrated dipole approximation, which is excellent for atom emitters, may break down in the case of quantum dots embedded in plasmonic nanostructures [1]. The proper description of quantum dot emission under such conditions comprises multipolar interaction terms that may be employed for enhancing light-matter interaction beyond the level possible for dipole emitters.

8425-16, Session 4

Dual-wavelength laser for Terahertz generation by photomixing

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Optical coupling between a photonic crystal membrane (PCM) resonant mode at a wavelength 0 and a standing vertical Fabry Perot cavity mode at the same frequency, where the former is inserted in the latter, has been recently investigated. It has been found, that such a system can provide strong photon-photon coupling leading to two new hybrid modes generation, whose energy difference is mainly determined by the overlap between the PCM-Bloch mode and the FP mode. The resulting dual-micro-cavity can be used for many applications in non-linear optics, taking advantage of the dual resonance to strengthen nonlinear effects. More specifically, we aim at providing dual-lasing micro-resonator for Terahertz generation using photo-mixing by associating it to a photoconductive device where the beating between both laser modes will occur. In this context optical gain will be provided either by III-V heterogeneous quantum well layers or quantum dots.

In this talk, analytical and numerical design rules are reviewed. Different design approaches using classical quarter-wave Bragg mirror and/or PCM reflector to build the dual-resonance micro cavity and their fabrication will be described. The tunability of the frequency separation between both modes using MOEMS technology will be discussed. As both optical laser modes will share common quantum gain medium, a dedicated numerical Monte Carlo analysis of the dual mode emission stability will be presented.

[1] “Dual-wavelength micro-resonator combining photonic crystal membrane and Fabry-Perot cavity”, Koku Kusiaku, Ounsi El Daif, Jean-Louis Leclercq, Pedro Rojo-Romeo, Christian Seassal, Pierre Viktorovitch, Taha Benyattou, and Xavier Letartre, Opt. Express.Vol. 19, No. 16, p.15255- 15264 (2011)

[2] “Multi-resonant microresonators for optical frequency conversion”, Koku Kusiaku, Xavier Letartre, Jean-Louis Leclercq, Pedro Rojo-Romeo, Christian Seassal, Pierre Viktorovitch , Proc. SPIE 7728, 77280K (2010).

[3] “Monte-Carlo simulation of laser diodes sub-poissonian light generation,” L. Chusseau and J. Arnaud, Opt. Quant. Electron., vol. 34, pp. 1007-1023, 2002.

8425-17, Session 4

All-optical dynamic frequency conversion in photonic crystal cavities

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The dynamic manipulation of light relies on the control of the transmission spectrum or dispersion of the light confining structure while the signal is still in the system. The light follows the modes of the structure as these are manipulated and thus its characteristics change accordingly, making effects such as light stopping and frequency conversion possible. The required fast modulation of the photonic structure can be achieved for instance through a refractive index change of silicon based upon the free-carrier plasma dispersion effect, the free carriers being generated either by linear or two photon absorption of a pump beam. In the first case the pump is incident on the structure from the direction perpendicular to the device plane.

We develop here the concept along with first experimental results for dynamic frequency shift of light by inducing a change of the refractive index of silicon through two photon absorption of a pump. Thus both pump and signal waves are guided in the structure. The key point consists in tailoring the structure such that the pump lifetime is shorter that that of the signal.

8425-18, Session 4

Optical trapping and assembly of particles by a nanocavity inside an optofluidic silicon chip

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Optical cavities miniaturized at the submicrometer scale enable both spatial and spectral confinement of an electromagnetic field at the nanoscale. This field localization leads to enhanced optical forces which promise future applications in the fields of optofluidics or optomechanics. In this work, we report optical trapping and assembly experiments of nanoparticles by photonic crystal nanocavities integrated on a silicon-on-insulator optofluidic chip. The fabricated optofluidic cells are designed to enable the real time control of optical control of the nanoresonator transmittance as well as the real time visualization of the nanoparticles motion in the vicinity of the nanocavity. We show that, for low input power (<0.1mW), the nanocavity behaves as a single particle detector whereas higher power leads to the formation of an optical tweezer. It is demonstrated that the trapped particles are arranged above the cavity in respect to the subwavelength structure of the confined electromagnetic field. Then, in light of the experimental optical near-field map of this confined field, we derive the distribution of the involved optical forces. Finally, we will discuss the dynamical interactions between the nanoparticles motion, the distribution of the cavity field and the strength of the resulting optical trap.

8425-19, Session 5

Photon and acoustic phonon coupling in phoxonic crystals

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Brillouin and acousto-optic interactions have traditionally been considered under a weak coupling regime for photons and acoustic phonons. The photo-elastic tensor is classically involved and the effect can be described by the interaction of three waves that satisfy both phase-matching and energy conservation. Two photons and one phonon are involved. The phonon frequency is much smaller than that of the two photons, but its wavelength is commensurate. More recently, the optomechanical effect has been shown to exist in cavities that confine simultaneously photons and phonons, providing an additional coupling mechanism.

The efficiency of opto-acoustic effects depends directly on the local energy density of the involved waves. There hence are two obvious directions in which to look for enhanced interactions: spatial confinement (for cavities and waveguides) and low group velocities (for waveguides). Spatial confinement has to be simultaneous for light and sound to be effective. The modal distributions of optical and acoustic waves should also be matched so that the interaction is optimized, a condition that depends both on the geometry of the nanostructure and on the choice of materials. Low group velocities are useful in order to increase the interaction time for a given interaction length.

The fascinating concept of the phoxonic crystal has appeared recently. The central “x” in the neologism “phoxonic” stands for “t” and “n” at once, meaning that a phoxonic crystal is simultaneously a photonic and a phononic crystal. In the literature, the term optomechanical crystal is also employed. The condition that is generally looked for is that a complete photonic and a complete phononic band gap are present simultaneously. The choice of materials and structure is of utmost importance in order to find an adequate phoxonic crystal configuration, and this quest has been the subject of many papers recently. We will review the properties of the different phoxonic crystal structures that have been proposed, including 2D and 3D crystals, 1D phoxonic crystal strips, and arrays of holes, pillars or resonators of the membrane type. We will also give an account of the ongoing experiments on such material systems as silicon and lithium niobate.

8425-20, Session 5

Guiding of high-frequency phonons through a phoxonic crystal

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We present an experimental study dealing with the excitation, the transport along a guide, and the localization inside a cavity, of elastic energy. The heterostructures consist in arrays of voids periodically drilled throughout silicon membranes and featuring a vacancy, or a line of vacancies. The lattices had either the honeycomb or the graphite symmetry. Some of these samples had repeat distances calculated to allow for both photonic gap centered on = 1.5 µm and phononic band gaps at a few GHz. Two all-optical experimental techniques both allowing for the generation of elastic waves and the monitoring of the displacements field inside the heterostructures and the defects are shortly described. Two regimes are investigated. First, narrow band elastic waves, whose central frequency is in the MHz range corresponding to resonance modes of the cavity, are generated. The optical probe allows for the measurement of the out-of-plane displacements associated to the elastic modes localized within the cavity or transmitted through the phononic structure. The spatial distribution of elastic energy inside the cavity is measured and compared with numerical predictions.

We then present the results we have obtained in the GHz regime. We have elaborated phonons guides with lengths ranging from a few µm to a few tens of µm. We have been able to optically excite broad band phonons on one side of the guide and to detect the elastic waves on the opposite side. When an aluminum grating deposited onto a taper is used to generate narrow band surface elastic waves up to 25 GHz, the phonons do not propagate over more than a few µm. Finally, we have excited into vibration phoxonic crystals featuring a cavity. We present the data we have recorded in the cavity itself.

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8425-21, Session 5

Acousto-optic interaction enhancement in dual photonic-phononic cavities

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Light control through elastic waves is a well established and mature technology. The underlying mechanism is the scattering of light due to the dynamic modulation of the refractive index and the material interfaces caused by an elastic wave, the so called acousto-optic interaction. This interaction can be enhanced in appropriately designed structures that simultaneously localize light and elastic waves in the same region of space and operate as dual optical-elastic cavities, often called phoxonic or optomechanical cavities. Typical examples of phoxonic cavities are multilayer films with a dielectric sandwiched between two Bragg mirrors or, in general, defects in macroscopically periodic structures that exhibit dual band gaps for light and elastic waves. In the present work we consider dielectric and metallodielectric particles as phoxonic cavities and study the influence of elastic eigenmode vibrations on the optical Mie resonances. An important issue is the excitation of elastic waves in such submicron particles and, in this respect, we analyze the excitation of high-frequency vibrations following thermal expansion induced by the absorption of a femtosecond laser pulse. For spherical particles, homogeneous thermalization leads to excitation of the particle breathing modes. We report a thorough study of the acousto-optic interaction, correct to all orders in the acousto-optic coupling parameter, by means of rigorous full electrodynamic and elastodynamic calculations, in both time and frequency domains. Our results show that, under double elastic-optical resonance conditions, strong acousto-optic interaction takes place and results in large dynamical shifts of the high-Q optical Mie resonances, manifested through multiphonon exchange mechanisms.

8425-22, Session 5

Phoxonic crystal sensor

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The basic concept of photonic and phononic crystal sensors is based on the measurement of changes in the transmission properties caused by changes of material properties of one of the materials building the crystal. It has been demonstrated that in the optical case the key parameter is the refractive index, in the acoustic case it is sound velocity. Both parameters can be measured with accuracy competitive with other optical and acoustic sensor principles. A phoxonic crystal sensor combines both concepts in one device, therefore allowing for a dual parallel determination of two independent material properties. Such a sensor is especially attractive for complex analytes as common in chemistry and biochemistry. We have designed and modeled a phoxonic crystal consisting of a solid matrix and holes where the central cavity acts as analyte container. In terms of the application of the phoxonic crystal as sensor we have concentrated on the generation of a characteristic feature in the transmission spectrum, actually a peak within the phononic and photonic bandgap (see figure) and have analyzed its sensitivity to material properties of selected liquids filling at least the central cavity. We could show theoretically that a defect, either created by a different diameter of the cavity (geometric defect) or by a different material filling the cavity (material defect) can realize a defect mode appearing within the bandgap as required for a simple sensing scheme. The respective wavelength/frequency of maximum transmission moves in accordance to the resonance conditions strongly related to speed of light and sound. Moreover, optical and acoustic energy can be confined in the defect resulting in a sharp isolated peak which is a requirement for wavelength/frequency resolution and hence high sensitivity.

8425-23, Session 5

Phononic and phoxonic crystal slabs sensors

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During recent years we have investigated the engineering of the dispersion curves and bandgaps in phononic and dual phononic-photonic crystal slabs and waveguides. Currently, we study their potentialities for sensing applications. In contrast to photonics-based sensors, little work has been devoted to phononic and phoxonic sensors. For this purpose, we study theoretically the existence of well-defined isolated features in the transmission spectra of such structures showing a high sensitivity to the sound velocity and refractive index of a liquid environment. A first geometry consists of a periodic array of grooves designed on a Si membrane and eventually covered with a second membrane. The grooves are empty or infiltrated with a liquid. The incident acoustic and optical waves are launched parallel to the slab. We define the best geometrical parameters to obtain well-defined peaks and dips in the transmission spectra sensitive to the properties of the liquid filling the grooves. Alternatively, we study a new geometry dealing with the transmission of acoustic and optical waves normally incident upon a phoxonic crystal membrane constituted by a 2D periodic array of holes in a silicon slab. We discuss the possibility of zeros of transmission, extraordinary transmission and Fano resonances which are tunable with the properties of the liquid surrounding the phoxonic crystal. Finally, we study the transmission characteristics of acoustic waves normally incident upon a structure constituted by a set of empty or filled cavities between two substrates.

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8425-24, Session 6

3D photonic crystals for photon management in solar cells

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Light management in single and multi-junction solar cells is becoming increasingly important to optimize the optical and electro-optical properties of solar cells. The limits of light path enhancements are discussed for non-resonant and resonant optical nanostructures as well as for angular-selective and energy-selective approaches. The potential of 3D photonic crystals for photon management in solar cells is discussed for the corresponding concepts and the state of the art is reviewed. Recent results on 3D photonic crystal intermediate reflectors and backreflectors for thin film solar are presented.

8425-25, Session 6

Tailoring the absorption in a photonic crystal membrane: modal approach

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Tailoring the absorption of a thin layer by using a nanophotonic structure is a key point for applications such as sensor or photovoltaic devices [1]. In this communication, we propose a method for achieving this goal in a photonic crystal membrane. For that purpose, we first applied Time Domain Coupled Mode Theory (TDCMT) [2] to such a membrane and demonstrated that 100% resonant absorption can be reached even for a symmetric membrane, using degenerate modes. This study highlighted the main role played by the coupling anisotropy of the modes and so of the photonic structure. Design rules were then derived from this model in order to tune the absorption in the system studied. Subsequently, Finite Difference Time Domain (FDTD) simulations were used as a proof of concept and carried out on a low absorbing material (extinction coefficient~10-2) with a high refractive index corresponding to the optical indices of hydrogenated a-Si (a-Si:H) in the near infrared. In doing so, 85% resonant absorption was obtained, which is significantly higher than the commonly reported 50% value. Then, we exploited our method, as an example, on thin layer *a-Si:H* photovoltaic solar cells that exhibit a broad absorption band around 600 nm [3]. The first goal is to explain this broad absorption band by discriminating the contribution of the modes involved. We finally report on a way of tailoring the absorption through the introduction of coupling anisotropy, which can be provided by an asymmetry of the membrane.

[1] S. Mallick, N. Sergeant, M. Agrawal, J. Lee, and P. Peumans, MRS BULLETIN 36, 453 (2011).

[2] C. Manolatou et al., Quantum Electronics, IEEE Journal of 35, 1322 (1999).

[3] G. Gomard et al., Journal of Applied Physics 108, 123102 (2010).

8425-26, Session 6

Absorbing photonic crystals for thin film solar cells

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A novel design which enables to enhance the absorption of the sunlight in an epitaxy-free monocrystalline silicon (c-Si) thin film solar cell is presented in this communication. It is based on the coupling of the incident light into the modes of a planar Photonic Crystal (PC) structure patterned in the absorbing layer.

The basic solar cell structure consists, from back to front, of a glass substrate, an aluminium layer, a 20 nm thick p-doped c-Si layer, a 1 µm mono c-Si layer, a 10 nm thick n-doped hydrogenated amorphous silicon layer, and a top transparent conductive oxide layer deposited at the end of the pattering processes. The top layers are patterned as planar PCs.

Electromagnetic simulations reveal a significant increase of the absorption with respect to the unpatterned stacks. One dimensional patterning of c-Si solar cells thus improves the absorption efficiency in the sole c-Si layer by 37%abs taking into account the AM1.5G solar spectrum between 300nm and 1100nm. Moreover, the absorption using two dimensions square lattice PC patterned stack is still 22%abs larger than the 1D PC, which also allows a polarization-independent behavior under normal incidence.

Based on these designs, we developed technological processes compatible with wide area patterning in order to fabricate such PC structures on the top of the solar cells. The active layers are patterned by combining laser holography, Reactive Ion Etching and Inductively Coupled Plasma etching.

The absorption spectra of those patterned cells are finally measured and highlight a significant enhancement, in compliance with simulation results.

Preliminary results on a more complex c-Si thin film solar cell will be presented, with front and rear structurations of different periods to confine much more light into the sole c-Si.

8425-27, Session 6

Optical field confinement effects on the absorption of compounds embedded in periodic nanostructured multilayers

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Herein we show experimental examples of localized photon modes in periodical multilayer structures.1,2 In the first example we show evidence of resonant photocurrent generation in dye sensitized periodically nanostructured photoconductors, which is achieved by spectral matching of the sensitizer absorption band to different types of localized photon modes present in either periodical or broken symmetry structures. Light confinement effects have been designed to match the desired absorption spectral range and thus selectively enhance the photon-to-electron conversion response to yield efficiencies up to 75% higher than that of a reference sample.3 The second experiment shows the spectral modification of the surface plasmon resonance of gold nanoparticles embed in a broken symmetry structure.4 This control was achieved through the changes in the photonic environment of the gold nanoparticles. Both results are explained in terms of the calculated spatial distribution of the electric field intensity within the configurations under analysis.

1. Calvo, M.E. et al. Adv. Func. Mater. 18, 2708-2715 (2008)

2. Colodrero, S., Ocaña, M. & Míguez, H. Langmuir 24, 4430-4434 (2008)

3. Anaya, M.; Calvo, M.E.; Luque, J.M.; Miguez, H. submitted

4. Sanchez-Sobrado, O. et al. Adv Mater, 23,2108-2112 (2011)

8425-28, Session 7

Anisotropic resonant scattering from polymer photonic crystals

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Polymer opals are polymeric self-assembled photonic crystals which display vivid structural colour generated by resonant scattering of light. Typical methods for optical characterisation of such materials do not capture the strongly angle-sensitive scattering, either ignoring it (conventional spectroscopy), averaging over all angles (dark-field spectroscopy) or being restricted to a plane of incidence (goniometry).

We have developed a hyperspectral goniometric technique allowing the full reconstruction of reciprocal-space scattering vectors from the complete angular scattering distribution, which reveals the strongly anisotropic nature of the scattering process at different frequencies.

The widths of the scattering cone, which dominates the perceived opal appearance, are found to be set by subtle disorder in layer spacing and by chain defects in the crystal lattice. The chain defects are introduced early in the edge-shear process used to produce polymer opals, and persist with further processing. These defects are thus crucial in the self-assembly process, and have a significant effect on the optical characteristics of the material.

Although it does not affect the chain defects in the structure, shear ordering enhances the visual appearance of the opals by increasing the scattering intensity. This is due to decreasing displacement of spheres about the average layer spacing, which leads to an increase in effective refractive-index contrast.

The observed structural colour of polymer opals may be further tuned by doping with absorptive carbon nanoparticles, which results in increased colour saturation. Decreasing absorption length in the material attenuates long multiple-scattering paths, and thus suppresses the wide-angle broadband scattering background.

The improved understanding of the role of disorder in the scattering properties of lower-contrast polymer opals leads to new processing techniques which advantageously tailor their optical properties for a wide range of applications.

8425-29, Session 7

Optical diffraction from opal-based photonic structures: transition from 2D to 3D regimes

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Synthetic opals are photonic crystals possessing stop bands in the visible spectral region due to the characteristic size of the silica particles of a few hundred nanometers. This offers a unique possibility for probing the photonic properties not only in the traditional way by measuring transmission or reflection but by directly observing diffraction patterns of light on a screen surrounding the sample. Here we report on experimental and theoretical investigations of light diffraction from opal films of different thickness.

We should emphasize two key features of the diffraction studies. First, an original technique of recording the diffraction patterns was used. In our setup the diffraction patterns are displayed on a cylindrical screen with a specimen fixed in its center. The diffraction reflexes are displayed on the cylinder surface in the full angle without any distortion. The second key feature is the experimental data presentation: a collection of a large number of the cylindrical screen color photographs is presented as a function of the light incidence angle and the angle of diffracted light registration. The advantage of this presentation is that one can easily distinguish 2D and 3D diffraction. The diffraction pattern for a 2D single layer in the considered coordinates consists of iridescent ovals. In contrast, the allowed 3D Bragg reflections in the considered coordinates will be represented by parallel iridescent straight lines.

The transformation of the diffraction patterns in the considered coordinates during the 2D-to-3D transition was studied experimentally and theoretically. With increasing number of layers, certain regions of ovals fade out and finally form straight lines typical for 3D diffraction. We also found that stacking faults in bulk opals lead to formation of a 2D-like diffraction pattern, i.e., such structure demonstrates 3D to quasi-2D transition in optical properties.

8425-30, Session 7

Interplay of Mie and Bragg resonances in partly ordered monolayers of colloidal particles

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It is commonly assumed that the synergy of collective and individual scattering in ordered arrays of particles promotes light localization and formation of photonic bandgaps. Moreover, Mie resonances are considered in tight-binding models as the origin of photonic bands. How good should be ordering to give rise to collective effects in scattering? Is it feasible to observe both Mie and Bragg resonances in the transmission/reflectance spectra of one and the same array? If yes, how the ensemble providing such possibility should look like? Apparently, no universal answer can be given. We addressed these questions experimentally by diluting 2-dimensional lattice of colloidal beads as an example.

The close packed 2D lattice of polystyrene beads shows the familiar diffraction pattern. Using bi-dimensional suspension of beads of very different diameters as a source for array crystallization, the spacing between beads was gradually increased. Thus the light transport was altered from the scattering-based to the one, which is partly based on hopping. Hence, both Bragg and Mie resonances were brought to one spectrum. The same approach was used to reduce the lattice ordering in few steps. Correspondingly, the balance between coherent and incoherent scattering was shifted to the latter and the Bragg resonances were progressively superseded by Mie resonances starting from short wavelengths. Important, the ripple structure of transmission spectra associated with Mie resonances once being revealed remains unaffected along the disorder increase. In contrast, the spectrum structure associated with the interference of incident and forward scattered light demonstrates the dependence on the disorder rate. Remarkably, the extinction curve calculated for the single bead reproduces quite well the Mie resonances of disordered array.

Based on these observations we will discuss the coupling of Mie and Bragg resonances in the formation of the photonic bandgap structure of diluted 2D arrays.

8425-31, Session 7

Tailored luminescent emission of dyes embedded in porous resonators

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Here we study the light emitted from different hybrid organic dye doped inorganic nanoparticle-based one dimensional (1D) photonic crystal (PC) architectures. The increase in the photon density of states caused by confinement in very specific slabs of the multilayer implies a lower photon group velocity,[1] which in turn yields longer light-matter interactions. We investigate both experimentally and theoretically[2] how the angular distribution of light emitted from these 1DPC structures is modified depending on the spectral matching of either resonant or stop band modes of the PC. Our measurements are explained in terms of the electromagnetic field distribution in the photonic structure. These results prove that by changing the photonic environment of a dye, it is possible to finely tune its optical response throughout the visible.

References

[1] Bendickson, J. M; Dowling, J. P.; Scalora, M. Phys. Rev. E, 1996, 53, 4107.

[2] Lozano, G.; Colodrero, S.; Caulier, O.; Calvo, M.E.; Míguez, H. J. Phys. Chem. C. 2010, 114, 3681.

8425-32, Session 8

Experimental demonstration of waveguiding in honeycomb and square-lattice silicon photonic crystal membranes

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Sub-micron crystal waveguides have been studied recently to obtain the confinement of elastic and optical waves in the same devices in order to benefit from their interaction. It has been shown that square as well as honeycomb lattices are the most suitable to produce simultaneous photonic and phononic band gaps on suspended silicon slabs [1]. The introduction of line defects on such “phoxonic” crystals should lead to an enhanced interaction between confined light and sound. In this work we report on the experimental measurements of light guiding through waveguides created on two-dimensional honeycomb- and square-lattice silicon photonic crystal membranes. The dimensions of the fabricated structures are chosen to provide a “phoxonic” bandgap, where the photonic bandgap occurs at wavelengths around 1550 nm.

To obtain the “phoxonic” bandgap, the silicon layer is a bit thicker that in conventional triangular-lattice photonic crystal (around 220 nm): 400 nm for the honeycomb and 325 nm for the square lattice. In both cases, we observe a high-transmission band when introducing a linear defect, although it is observed for TM polarization in the honeycomb lattice (odd symmetry bandgap) and for TE polarization in the square lattice (even symmetry bandgap). Computations using the plane-wave expansion and the finite element methods [2] permit us to say that the guided modes are below the light line and, therefore, lossless up to fabrication imperfections. We also observe how the high-transmission region associated to the lossless guided modes is shifted when modifying the parameters of the fabricated samples.

Our results lead us to conclude that waveguides implemented in honeycomb and square lattice “phoxonic” (or optomechanical) crystals are a very suitable platform to observe an enhanced interaction between propagating photons and phonons.

[1] Y. Pennec et al., Opt. Express 18, 14301 (2010)

[2] V. Laude et all., Opt. Express 19, 9690 (2011)

8425-33, Session 8

Experimental demonstration of light bending effect at optical wavelengths in a non-homogenizable graded photonic crystal

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Controlling light paths and beam profiles of guided waves in planar optical structures has received a strong interest for some years. The main proposed approach relies on the use of metamaterials. Coupled with the formalism of transformation optics, this method has led to several works showing the possibility to mold the flow of electromagnetic waves in almost arbitrary shape waveguiding structures. However, strongly anisotropic metamaterials with complicated permittivities and permeabilities are needed at optical frequencies, while strong losses are induced by the use of metals. For these reasons, experimental results have been mostly obtained by reducing the target to the use of broadband all-dielectric structures, i.e. by relying on sub-wavelength dielectric structures to control the local average refractive index of planar optical waveguides.

We present here modeling and experimental results of field bending at optical wavelengths based on another approach relying on a non-homogenizable graded photonic crystal. A square lattice planar photonic crystal (PhC) made of a two-dimensional chirp of the air-hole filling factor is exploited. The sensitivity of light paths to wavelength tuning is then exploited to show demultiplexing capability with low insertion loss and low crosstalk. Experimental results are in good agreement with the prediction that had been performed using the equations of Hamiltonian optics and Finite-Difference Time-Domain simulations. This experimental demonstration opens opportunities for light manipulation and applications in photonic circuits using a combination of unusual dispersive phenomena in PhCs and additional degrees of freedom brought by a generalized two-dimensional chirp of PhCs lattice parameters.

8425-34, Session 8

Photonic crystal waveguide created by selective infiltration

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The marriage of photonics and microfluidics (“optofluidics”) uses the inherent mobility of fluids to reversibly tune photonic structures beyond traditional fabrication methods by infiltrating voids in said structures. Photonic crystals (PhCs) strongly control light on the wavelength scale and are well suited to optofluidic tuning because their periodic air-hole microstructure is a natural candidate for housing liquids. The infiltration of a single row of holes in the PhC matrix modifies the effective refractive index allowing optical modes to be guided by the PhC bandgap. In this work we demonstrate optofluidic single row defect waveguides.

We present an experimental demonstration of a reconfigurable single mode W1 photonic crystal defect waveguide created by selective liquid infiltration. We modified a hexagonal silicon planar photonic crystal membrane by selectively filling a single row of air holes with high refractive index ionic liquid. The modification creates optical confinement in the infiltrated region and allows propagation of a single optical waveguide mode. We describe challenges arising from the infiltration process and the liquid/solid surface interaction in the photonic crystal. We include a detailed comparison between analytic and numerical modeling and experimental results, and introduce a new approach to create an offset photonic crystal cavity by varying the nature of the selective infiltration process.

8425-35, Session 8

Zero-average index metamaterials and zero-average dispersion curvature photonic crystal superlattices for self-collimation of light

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Bragg mirrors including positive and negative index layers have recently attracts much attention owing to their novel optical properties. These 1D photonic crystals (PhCs), consisting of periodically set metamaterial layers of negative index and positive index layers (such air-layers), have reveal an intriguing photonic band gap of unique properties. This gap called zero-n gap is insensitive with respect to the period scaling, random or light polarization and it arises when the average optical index is null over one spatial period1-2. This zero-n gap has also been demonstrated in PhC superlattices at the near infrared frequencies. These structures alternate homogeneous layers and 2D PhCs layers of negative effective index that mimic metamaterials properties3-4.

We will show that beam shaping operations can be realized in zero-average index metamaterials when an additional optical condition is met. Surprisingly, even if these Bragg mirrors present a null average index, they can support resonant modes lying in the zero-n gap that enable self-collimation or focalization of light5. However, resonant self-collimation in zero-average index materials may be difficult to obtain since it requires to simultaneously satisfy numerous optical conditions that can be hard to achieve in an experimental set-up. Then, we will demonstrate that self-collimation in feasible PhC superlattices is also possible without the zero-average index condition. For that purpose, we will show that diffraction-free beams are propel over hundred of microns when a spatial dispersion compensation mechanism holds. Numerical results guided by a beam propagation theory show that original PhC superlattices of very low filling factor in air (3%) can be designed6. These versatile devices enable in addition to combine slow light and self-collimation effect, properties unachievable in common 2D PhCs. Finally, PhC superlattices provide new perspectives for enhancing light-matter interaction in the self-collimation regime.

8425-36, Session 8

Woodpile photonic crystal for beam collimation

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We describe beam propagation behind the Photonic Crystal due to the negative diffraction in the structure. We report first experimental observation of the formation of a narrow, well collimated laser beam behind the three-dimensional Photonic Crystal of a woodpile type. Our samples of woodpile Photonic Crystals were fabricated with a femtosecond laser multi-photon polymerization technique by direct three-dimensional writing in polymers with up to 200 nm spatial resolution. We used two different kinds of samples: of high contrast and of low contrast. The low contrast samples had longitudinal period of 4.5 micrometers, while high contrast samples had longitudinal period of 4.1 micrometers The transverse period was 1 micrometer for both types of the samples.

8425-37, Session 9

Resonant photonic crystals and quasicrystals

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Photonic crystals are the structures where the periodic spatial modulation of the dielectric constant leads to the Bragg diffraction. Resonant photonic crystals present a special class of such systems, where one of the components is characterized by a resonant optical response. We will focus on the photonic crystals based on the multiple quantum well (QW) structures QW/B/QW/B..., where B are the barriers. Each QW hosts a resonance of the quasi-two-dimensional exciton. Barriers are sufficiently thick so the excitons can not tunnel between different QWs. However, QWs are efficiently coupled by light. Eigenmodes of such system are excitonic polaritons. The advantage of QW-based systems is the possibility to control the optical spectra by applying electric or magnetic field, shifting excitonic resonance frequency.

We will discuss the Bragg quantum well structures, where the barrier thickness equals to the half of the light wavelength at the exciton resonance. The constructive interference of the waves reflected from different QWs leads to the Bragg enhancement of the reflectivity and to the formation of the superradiant mode of the excitonic polaritons. The radiative decay rate of superradiant mode is proportional to the number N of the QWs. Recent theoretical progress for such systems will be discussed. We will present discuss the time-domain response of the multiple QWs to the short optical pulses. We will review recent experimental results obtained in Ioffe Institute at different temperatures.

Periodic QW structures will be confronted with Fibonacci photonic quasicrystals, based on the QWs sandwiched between the two types of barriers, A and B, forming the Fibonacci sequence ABAABABA... Quasicrystals are ordered, but non-periodic. Still, the long-range-order allows for the Bragg diffraction in quasicrystals. We will show, how the Bragg diffraction in Fibonacci QW quasicrystals leads to the superradiant coupling of the QWs. Analytical theory based on the two-wave approximation and describing these effects will be discussed. The quasicrystals also reveal a number of intriguing phenomena absent in periodic medium such as localized states of light and self-similar reflection spectra. The one-dimensional quasicrystals will be also compared with the two-dimensional ones, based on the Penrose lattices of quantum dots. We will show how the light diffraction on the Penrose grating leads to the novel type of the Wood anomalies, absent for the periodic structures.

8425-38, Session 9

Bistable photonic nanostructures based on molecular spin crossover complexes

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Spin crossover (SCO) complexes of transition metal ions represent an important class of bistable materials for which switching between high-spin and low-spin electronic configurations can be obtained by diverse external stimuli such as temperature, pressure, light irradiation, magnetic fields or even the adsorption of gas/vapour molecules. The switching of molecular spin-states is accompanied with a spectacular change of various physical properties. For this reason the possible applications of these materials, including information storage, display and switching devices, pigments and sensors continue to draw much attention. Up to now, efforts have been focused primarily on magnetic susceptibility and color changes. On the other hand, the refractive index changes associated with the SCO provide also interesting prospects for a range of photonic applications. The relevance of this property has been less widely recognized, probably due to the lack of suitable thin films and photonic structures exhibiting SCO.

In this presentation we will describe a simple, but efficient method to elaborate thin films and nano-patterns of spin crossover complexes using spin coating and soft lithography, respectively. These SCO nanostructures can respond reversibly to various external stimuli with fast response times. The response can be either transient (gating) or non-volatile (switching) - depending on the experimental conditions. We believe that these assets provide a very appealing scope for tunable SCO devices in a variety of applications including optics, photonics and chemical sensors. In particular, we will present three photonic application principles:

1. We have shown that surface plasmon polariton waves propagating along the interface between a metal and a spin crossover layer can be used to detect the spin state changes in the latter with high sensitivity even at the nanometer scale. This finding opens up the possibility to use spin crossover thin films to modulate the propagation of electromagnetic waves in plasmonic or other type of guided wave devices.

2. Surface-relief diffraction gratings have been also fabricated from spin crossover complexes and a significant effect of the molecular spin state change on the grating diffraction efficiency has been demonstrated. Using transmittance theory, the variation of the diffraction efficiency can be traced back quantitatively to the considerable refractive index change accompanying the SCO. This latter occurs primarily due to the molecular volume change associated with the SCO.

3. We have also investigated SCO thin films and nano-objects with luminescent doping. The luminescence intensity was found to change significantly upon the spin transition - owing to a radiationless energy transfer process between the transition metal ions of the complex and the luminophore. In particular, we have been able to follow the spin state changes even in individual nano-objects down to 100-150 nm. These nano-objects have a great potential to be used as localized sensors for nano-thermometry applications.

8425-39, Session 9

Hybrid architectures: towards enabling 4-dimensional plasmonic-photonic crystals

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Light transport in recently introduced hybrid plasmonic-photonic crystals is controlled by several resonance mechanisms that offer incredible opportunities for engineering the optical response in frequency, space and time domains. Using this enabling technology we developed complex structures combining plasmonic and photonic crystal components with the aim to enhance hybridization of Bloch modes and surface plasmon polaritons.

Sandwich structures consisting of hexagonally packed monolayers of colloidal spheres separated by thin metal films were prepared and their optical transmission/reflectance spectra were examined. Both experiments and models point to the strong coupling between surface plasmon polaritons and eigenmodes of photonic crystals that gives rise to hybrid modes possessing fast and slow group velocities.

Complexity of hybrid architectures is translated into complexity of hybrid's optical properties. Some features, like splitting of the extraordinary transmission peak in proportion to the number of interacting metal films, can be associated with cross-coupling between surface plasmon polaritons located in adjacent metal films. Other features, like avoided band crossings, can be interpreted in terms of the plasmonic bandgap structure. Besides, we observed the strong absorption band at the spectral range of the localized plasmon resonance in metal semi-shells. Important, optical spectra can be widely tuned by changing the structure.

Coexistence, spatial separation and coupling of fast and slow modes provide conditions for inhomogeneous light transport in hybrid architectures, especially in the case of embedded asymmetry. Hence, different electromagnetic modes simultaneously excited at the one end may propagate with different velocities giving rise to periodical variation of the field pattern along the light path. Alternatively, under the pulse excitation the output field pattern will evolve in time that makes hybrids time-dependent 4-dimensional photonic crystals.

We will discuss the hybrid architectures and emphasize the unique features in optical transmission/reflectance spectra acquired in cw regime that support our point of view.

8425-40, Session 9

Ultrafast dynamics of Faraday rotation in magnetic photonic crystals

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A short light pulse propagating through a magnetic medium can demonstrate a nonlinear time dependence of Faraday rotation, if the medium optical width is comparable with a pulse length. The effect arises from a non-reciprocity of the Faraday rotation and multiple interference inside the medium. In this paper, the ultrafast temporal behavior of Faraday rotation is observed in magnetophotonic crystals by using a polarization-sensitive cross-correlation technique. One of the key features of photonic-band-gap materials is a possibility to achieve a very small light group velocity at the photonic bang-gap edge and at the defect mode. This leads to a row of bright “slow-light” phenomena and promising applications such as enhancement of nonlinear-optical and magneto-optical effects.

A femtosecond fiber laser with 70-MHz repetition rate, average intensity of 130 mW, pulse duration of 150 fs is used as a source of radiation in the cross-correlation scheme. A Glan prism splits an incoming laser pulse into two orthogonally polarized beamlets. One of them goes through the sample placed in magnetic field. Both pulses are then focused at the same spot into a crystal with a (2) nonlinearity for noncollinear second-harmonic generation. Its intensity is detected by a photodiode at a magnetic field frequency as a function of the time delay. The cross-correlation function contains information about polarization rotation time dependence.

The resulting dynamics in magnetic photonic crystals and microcavities depend on spectral position of pulse central wavelength. If light electric field is localized at a defect mode then the resulting magnitude of Faraday rotation would be negligibly small until the time when first pulse came out of structure. This time delay could be in order of 100 fs. In case of photonic band-gap edge position one may obtain an oscillation Faraday rotation as a function of time.

8425-49, Poster Session

Band-edge lasing and mini-band lasing in 1D dual-periodic photonic crystal

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Herein, holographic rhodamin 6G-doped dichromated gelatin (DCG) was used for creating low-threshold photonic band-edge lasing (PBEL). Experimental and theoretical analysis of light-matter interaction with different excited citation of band in 1D photonic crystal (PC) was shown in this paper. We considered almost every condition including in-band, out-of-band and near the band edge while keeping the local density of optical states (LDOS) unchanged. Theoretical calculations were also made to simulate the excitation-angle dependence of the effective gain in the PC, which agreed well with the experiment. Results show that the PBEL intensity and pump efficiency are sensitive to the excitation angle, enhanced obviously at the excitation near the band edge and suppressed distinctly in the band which agreed well with the theoretical prediction. 42-fold enhancement emission intensity and 665-fold high pump efficiency were observed when pumped at the band edge, compared with pumped in the band gap. Lasing actions excited at near high-energy and low-energy band edge were observed simultaneously, and their full widths at half maximum were 3nm and 5nm, respectively. From the properties of two different band edges pumping, we also demonstrated that the active matters can diffused not only in the air voids but also in the high index region of the gelatin.

To get more quality resonators, 1D superstructure by four-beam interference holography and 1D moiré structure by re-exposure holography were fabricated in our work. The measured transmission spectra show that mini-band states have been evidently located in the forbidden gap, with high Q factors of 55, 120.5 and 103 for band1, band 2, band 3, respectively. Based on Transfer Matrix Method (TMM) and non-uniform correction, numerical simulations of transmission spectra agreed well with the experimental results. The localized modes can be seen as band-edge states folding and split off into shallow levels by the long-period modulation, and the EM field localized in the whole multilayer regions. Compared with the band-edge state, these mini bands have stronger slow-light effect and weaker second order dispersion of group velocity. The electric intensity is localized in the whole multilayer region within the center frequency of mini bands. Combining with the properties of DCG 1D PBEL, these structure provides potential application in fluorescence detecting and Bioluminescence probing.

8425-50, Poster Session

Investigation the effect of shapes, size, and orientation of dielectric rods on the photonic band gap for various lattices in 2D anisotropic photonic crystals

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The photonic band structures of two-dimensional anisotropic photonic crystals have studied by solving Maxwell's equetions with use of the plane-wave expansion method.

Three distinct theoretical approaches are pursued: the calculation of photonic bands and density of states, and of modes in the gap associated with line and point defects; the calculation of optical properties like reflection, transmission and diffraction; numerical simulation of the propagation of electromagnetic waves in photonic crystals, including the effects of disorder.

We have calculated the photonic band structure for electromagnetic waves in a structure consisting of a periodic array of parallel dielectric rods of various cross sections, whose intersections with a perpendicular plane form a different shape of lattice.

We reveal that a maximum absolute band gap for these structures is achieved for an intermediate rotation angle of the rods. This angle depends on the radius of the rods and the refractive index of the background material.

It has recently been reported that the symmetry reduction of atom configuration by introducing two-point basis set in simple 2D lattices can remarkably increase absolute band gaps. Owning to different refractive indices for electromagnetic waves with E and H polarization, the band gaps for the two polarization modes can be freely adjusted and matched to overlap optimally. The anisotropy in atom dielectricity can break the degeneracy of photonic bands and remarkably increase absolute band gaps. We prefer to choose the extraordinary axis of uniaxial crystal parallel to the extention direction of rods with a positive anisotropy.

We considered three type of lattice (triangular, square and Hexagonal) with anisotropic tellurium rods in air background with different geometric shapes (oval, circle, square, hexagon and rectangle).

The numerical results show that the overlap photonic band gap (PBG) between the TM and TE gaps (polarization-independent PBG) is the largest for a triangular lattice of oval rods with 0^°orientation.The overlap PBG for a square lattice of rectangular rod with 150^° orientation is the next largest.

An important result is that compared to isotropic photonic crystals, which maximum photonic band gap is achieved by selecting a rod of the same symmetry with lattice; this inference is not true in the case of anisotropic crystals.

8425-51, Poster Session

Microwave properties of nonlinear one-dimensional quasiperiodic photonic crystals

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The nonlinear properties of quasi-periodic photonic crystals based on the Thue-Morse and Fibonacci sequence are investigated. We address the transmission properties of waves through one dimensional symmetric Fibonacci, and Thue-Morse system i.e., a quasiperiodic structure made up of two different dielectric materials (Rogers and air), in quarter wavelength condition, presenting in the one directions. The microwave spectra are calculated by using trace map method in normal incidence geometry. In our results we present the self-similar features of the spectra and we also present the microwave properties through a return map of the transmission coefficients. We extract powerfully the band gaps of quasi-periodic multilayered structures, called `pseudo band gaps' often contain resonant states, which can be considered as a manifestation of numerous defects distributed along the structure . Taken together, the above two properties provide favorable conditions for the design of an all-microwave reflector.

8425-52, Poster Session

Fabrication and characterization of three-dimensional metallodielectric photonic crystals for infrared spectral region

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To date, the interference lithography in which the photoresist is exposed to a 3D interference pattern presents a promising fabrication technique. The interference lithography allows to produce photonic crystal (PhC) templates up to ~50 lattice periods thick with less than 5% attenuation through the thickness of the film.

Polymeric PhC lattices are unable to have complete band gaps because of the low value of the polymer refractive index. For the purpose of obviating this problem, a number of authors have proposed that the polymeric lattice should be coated with a metal layer. Among the materials exhibiting photonic band gap, metallic PhCs and metallodielectric PCs attract significant interest. In metallodielectric PhCs, discontinuities of the dielectric function at the metal-dielectric interface are much stronger than in dielectric PhC, and consequently, significant photonic band gap attenuation can be attained in smaller structures comprising fewer lattice periods.

We propose a technique for the realization of three-dimensional metallodielectric photonic crystals based on fabricating polymeric structures using the interference lithography followed by the magnetron deposition of a gold nanolayer.

To form a 3D polymeric PhCs lattice in the photoresist by interference lithography, we used a triple exposure of the photoresist film to a two-wave interference pattern. The polymeric array was recorded using a He-Cd laser of wavelength 442 nm in SU-8 photoresist. Using the magnetron deposition (SPI-Module Sputter Coater, USA), a 50 nm thick golden layer was deposited onto the PhC. The layer thickness was measured by a quartz thickness monitor. The optical properties of the PhCs were studied on an FT-IR Hyperion 1000 microscope with a FT-IR spectrometer Tensor 27 (Bruker Optics, Germany), using which we measured the reflection coefficients of the structures under study. Numerical modeling of the PhC optical reflectivity were performed with the finite-difference time-domain (FDTD) method using a freely available software package. The reflectivity was calculated by modeling propagation of a plane wave incident on the PhC along the z-axis direction and comparing the intensities of reflected and incident waves. The spectrometry and FDTD modeling data show that there is a photonic band gap centered at the wavelength approximately equal to the photonic crystal period. As such, the method provides a flexible new route to novel metallodielectric PhCs and integrated devices having optical function in IR region of the electromagnetic spectrum.

8425-53, Poster Session

Electrically tunable photonic films for large area display

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Electrically tunable photonic films exhibiting full colors have been demonstrated using core-shell photonic colloids. The magnetic core and surface modified shell layer by sol-gel process allow the stable dispersion of colloidal ink. Thin films of colloids were deposited on indium tin oxide (ITO) coated glass. Upon the application of an external magnetic field, colloids are assembled to form a photonic structure and fixed by UV light. The optical properties of fixed photonic films could be further tuned by controlling driving voltage. We anticipate that our results will suggest design rules for photonic display devices based on photonic crystals. In particular, the features of our photonic pixel, such as tunable volatility of photonic color, broad range of color expression, low drive voltages, and easy fabrication, are promising for epaper applications.

8425-54, Poster Session

Micro- and nanoscale photonic lattices induced by Bessel beam technique in doped lithium niobate crystals

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In this report we present the results of the optical induction of 1D and 2D micro- and nano scale annular symmetry photonic lattices in single and doubly doped photorefractive lithium niobate (LN) crystals by Bessel beam technique developed in [1]. The non-diffracting Bessel beam was formed by axicon and counter-propagating Bessel beam (CPBB) geometry was used for build-up of the Bessel standing wave. The cw single mode 532nm, 17mW laser beam and 2mm thick LN crystals doped by Fe and doubly doped by Fe:Cu with 0,05wt% of impurity ions were used for lattices recording during 60min. The non-uniform intensity distribution of the beams was imparted into the irradiating photorefractive medium via electro-optic effect thus creating refractive index photonic lattices. The Bessel beam has no intensity modulation along the propagation Z axis and the concentric ring pattern of the single Bessel beam provided the recording of annular 1D photonic lattices with a radial period of 10μm in LN crystals. CPBB geometry builds up the Bessel standing wave with periodic annular structure in each anti-node thus recording 2D photonic lattice in the crystal. The lattice is a combination of annular and planar gratings with 10μm period in the radial and half-wavelength 266nm period in axial directions. The recorded lattices were tested by diffraction of probe laser beam at 633nm on the lattices. The direct observation of the recorded lattices by phase microscope was also performed.

The crystals with optical C-axes, oriented along and perpendicular to the crystal surface (Y-cut and Z-cut LN crystals, were used for photonic lattices recording. The far field transmitted diffraction pattern consists of two oppositely disposed segments of a ring for Y-cut LN crystal while it is a whole ring for Z-cut crystal. Further observation by phase microscope showed that the contrast of the recorded lattice has pronounced azimuthal dependence. Such difference is a result of predominant modulation of extraordinary refractive index along the C-axis of the crystal, which, in turn, concerns the predominant migration of the electrons due to the photovoltaic effect along the C-axis of the crystal. For Y-cut crystal with vertical directed C-axis, the probability of migration and final trapping of electrons in dark zones is larger in the central vertical stripe compared with periphery because the distances between the bright and dark neighboring circles in the periphery are larger compared with the central vertical stripe of Bessel beam structure. This leads to the azimuthal dependence of the contrast of the recorded lattice.

The photonic lattices recorded in LN:Fe:Cu crystals showed high stability against erasure during readout by weak probe beam at the recording wavelength. Under illumination by 2mW probe green beam the total erasure of the grating occurred after 8000sec, which was controlled by measuring the diffracted beam power during readout. The destruction of the lattices recorded in LN:Fe crystal takes several minutes.

Annular symmetry photonic lattices are promising as guiding and trapping systems, for spatial optical soliton formation, in optical communications devices etc.

REFERENCES

[1] A. Badalyan et al, Proceedings of SPIE, Vol. 7996 (SPIE Bellingham, WA, 2011) 799611-1-9.

8425-55, Poster Session

Photonic crystal sensor for simultaneous strain detection on orthogonal directions

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In this paper we present a photonic crystal cavities strain sensor for simultaneous detection on two orthogonal directions.

The sensor is constituted by a 2D photonic crystal waveguide demultiplexer [1] with two orthogonal output channels. On each channel is a cavity resonant at frequency f1 and f2, respectively, with f1 belonging to the channel 1 frequency band and f2 belonging to channel 2 frequency band.

The sensitive elements used are the cavities optical length variations due to the substrate strain, simultaneously measured by means of the cavities detuning by radio-frequency phase modulation of the impinging laser light. This techniques was widely demonstrated in the last years [2] [3] and initially borrowed by the cavity frequency stabilization and locking Pound-Drever-Hall methods [4].

In fact the lattice strain, due to the substrate deformation, induces a detuning of the cavities resonance respect to the unperturbed condition. By suitable design of the cavities, each of latest results more sensitive to the strain along his major axis, so that the orthogonal configuration allow to discriminate the strain along two orthogonal directions. The simultaneously measurement of the strain on both directions is enabled by the interrogation technique, by suitable design of the cavities. The latest, indeed, are designed to have equal linewidths, g, narrower than each demultiplexer channels bandwidth. In this way, if a two wavelengths laser light at frequencies f1 and f2 , phase modulated at frequency W>g , enters the devices input channel, it is separated such that the signal with carrier at f1 will be reflected by the cavity 1 and the other one by the cavity 2. If the modulation frequency W is such that the sidebands fi+W and fi-W (with i=1,2) of each carrier remain in the corresponding demultiplexer channel frequency band, depending on the cavity detuning, the reflected sidebands will experience a very different phase shift while at cavity resonance they are completely out of the phase. Therefore, demodulating at frequency W the carrier at frequency f1, we extract information only on the detuning of the cavity 1; while demodulating the signal at wavelength f2 we can draw out the detuning of the cavity 2.

The studied configuration allows to realize a very compact device that can be placed far from the interrogation signal generation apparatus and the detection apparatus, and linked to the latest by means of the unique interrogation channel (input/output channel), since the monitored signals are the cavities reflected signals).

The appeal of such type of devices, respect to the corresponding ones in optical fibers, is its compactness an the possibility to expand the configuration to create on the same chip the detector and the requested signal processing devices.

The sensor is analyzed by means of the cavities theory and by finite difference beam propagation methods with an introductory study on the simultaneous detection of the detuning of two cavities by means of Drever-Pound-Hall technique.

REFERENCES

[1] Djavid, M. and Ghaffari, A. and Monifi, F. and Abrishamian, M.S. T-shaped channel-drop filters using photonic crystal ring resonator Physica E: Low-dimensional Systems and Nanostructures, vol. 40, n 10; 3151-3154, 2008

[2] J.H. Chow, I.C.M. Littler, G. De Vine, D.E. McClelland, and M.B. Gray. Phase-sensitive interrogation of fiber bragg grating resonators for sensing applications. Lightwave Technology, Journal of, 23(5):1881-1889, 2005.

[3] G. Gagliardi, M. Salza, P. Ferraro, and P. De Natale. Fiber Bragg-grating strain sensor interrogation using laser radio-frequency modulation. Optics Express, 13(7):2377-2384, 2005.

[4] G. Gagliardi, M. Salza, P. Ferraro, and P.D. Natale. ''Interrogation of FBG-based strain sensors by means of laser radio-frequency modulation techniques" Journal of Optics A: Pure and Applied Optics, vol.8;S507,year={2006} t

[5] RWP Drever, J.L. Hall, FV Kowalski, J. Hough, GM Ford, AJ Munley, and H. Ward. ''Laser phase and frequency stabilization using an optical resonator.'' Applied Physics B: Lasers and Optics, 31(2):97-105, 1983.

8425-56, Poster Session

Double cavity refractive index photonic crystal sensor temperature calibrated

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In this paper we present an integrated double branch cavities refractive index sensor calibrated in temperature and integrated in each of two output channels of a wavelength demultiplexer. The studied configuration allows to realize a very compact device with only one interrogation channel, since the monitored signals are the cavities reflected signals. The sensitive elements used are the modulation of the cavities linewidth due to temperature and refractive index change, measured by means of the cavities detuning.

The appeal of such type of devices, respect to the corresponding ones in optical fibers, its compactness and the possibility to expand the configuration to create on the same chip other signal processing devices. The reliability of the proposed configuration is related to the interrogation technique, based on the radio-frequency phase modulation of the impinging laser light. This techniques was widely demonstrated in the last years and initially borrowed by the cavity frequency stabilization and locking Pound-Drever-Hall methods.

The sensor is constituted by two cavities, with the same linewidth and different resonance frequencies, f1 and f2, respectively, placed on each output channel of a wavelength demultiplexer designed in a holes photonic crystal lattice. Only one cavity is such that can be filled by an infiltrated fluid, to feel the refractive index change, while the other one constitutes the temperature reference.

In this way, by interrogating the sensor with a double frequency components light at f1 and f2, suitably phase-modulated at frequency W, greater than the cavities linewidth, and such that the sidebands of each carrier remain in the corresponding demultiplexer channel frequency band, we monitor on a single channel simultaneously the detuning of both cavities.

In fact, since passing through a phase modulator driven at frequency W, the incoming laser light will presenttwo carriers at the laser frequency f1 and f2 with the respective two sidebands at frequency fi- W and fi+W (with i=1,2), being the modulation frequency of the order or greater than the cavities linewidth, depending on the cavity detuning, the reflected sidebands will experience a very different phase shift while at cavity resonance they are completely out of the phase.

In this way, demodulating with the same frequency W the reflected signal at frequency f1, we extract information only on the detuning of the cavity 1; while demodulating the signal at frequency f2, t we can draw out the detuning of the cavity 2.

This scheme allows to design a refractive index sensor calibrated in temperature that can be interrogated by means of only one channel, since the two signals can be extracted from the sensor through the same input/output channel and then separated with optical filter to be separately detected and demodulated.

The interesting on this configuration is that the sensor can be placed far from the detection and interrogation apparatus, being connected to these only by means, for example, of an optical fiber.

The sensor sensitivity and capabilities are investigated by means of the cavities theory and by finite difference beam propagation methods.

8425-58, Poster Session

Diffraction-compensated dispersion-accumulated superprism based on two cascaded photonic crystals

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The benefits of unusual dispersive properties of photonic crystals (PhCs) are often mitigated by phenomena like spatial broadening of propagating beams. This problem is usually solved using millimeter long conditioning regions to pre-compensate for beam spreading. An approach is explored here to manage the strong diffraction of photonic superprisms without long pre-conditioning regions. Unconventional photonic crystal lattice cells are engineered using Plane Wave Expansion simulations, and two PhCs having both positive dispersions but diffraction properties of opposite signs are chosen. The method developed for this is based on the calculation of the Equi-Frequency Surfaces and post-calculations achieved to calculate dispersion (q factor) and diffraction (p factor) parameters in the whole reciprocal space of various PhC configurations. Light propagation in the combined photonic structure is studied using Finite Difference Time Domain simulation to validate the predicted dispersion accumulation and diffraction compensation approach. To demonstrate the interest of this architecture, we first placed the negative-p PhC and the positive-p one after. Similar diffraction compensation and dispersion addition effect could be obtained in the reverse configuration. Beyond the topic of the explored configuration, this works aims at showing that approaches relying on the combination of several PhC areas to compensate or tune unwanted dispersion phenomena may serve to the design of optical integrated functions.

8425-59, Poster Session

Beam combining of low-loss tapered photonic crystal fibers bundle

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Photonic crystal fibers (PCFs) have attracted much attention in recent years due to the unique waveguide properties that are vastly different from those of conventional fibers. The capabilities of the PCF can be extended and enhanced by tapering significantly. In this paper, the fabrication and characterization techniques of tapered PCFs are introduced, and the beam combing with tapered array of photonic crystal fibers is also presented for the purpose of pump power combing in fiber lasers and amplifiers. Using "fast and cold" method, the tapered PCFs combiner is fabricated without collapsing the air-holes, namely, the cross-sectional structure of the PCFs are scaled down proportionally. The taper shape and taper ration are governed by the local heat distribution, the pull-rate, and the gas pressure inside the air-holes. Hence, the combiner can be designed to follow adiabatic criterion to be low-loss. The PCF can be operated at single-mode regime and the brightness of the taper PCFs bundle is conserved. The power transfer efficiency exceeds 90%. The M-square value of the combined beam is close to the theoretical limit. Therefore, tapered photonic crystal fibers bundle is confirmed to be a rugged device for high brightness and high efficiency beam delivery.

8425-60, Poster Session

Group delay tuning in three-beam interferometers: an alternative to photonic crystals for generating slow and fast light

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The promising applications of slow and fast light (SFL) systems for optical communications has fostered intense research in this field within the photonics community. Reports on abnormal pulse propagation regimes comprise a wide range of optical systems, like active media, non-linear media and photonic crystals. Photonic crystals are linear and passive structures which have proved particularly interesting for group delay tuning applications, with superluminal propagation for a pulse with center frequency in the bandgap and subluminal propagation at the defect mode. Recently, an equivalent linear and passive structure exhibiting also band gaps and defect modes was reported for SFL applications. It consists in a series connection of Mach-Zehnder interferometers of totally homogeneous material. In this work, we explore an alternative way of generating SFL regimes in a linear and passive interferometer-based system. We demonstrate the occurring of such propagation regimes in linear and passive 3 beam interferometers for center pulse frequency close to their transmission minima. We show that the group delay can be tuned from subluminal to superluminal (and even negative) values by simply changing the length of one of the interferometer's arms. We have built our interferometers using 50-Ω coaxial cables and 1x3 power splitters in order to perform the experiments in the radiofrequency (RF) range. Nevertheless, the proposed interferometers are scalable to other frequency ranges because of the universality of the wave interference phenomena, and their implementation in the optical range could be feasible by means of MOEM or optical fiber technologies. A great advantage of working in the RF range is that the structures can be fully characterized in the frequency domain by measuring their scattering (S) parameters with a two-port vector network analyzer. Group delays are then obtained from the derivative of the transmission (S21 parameter) phase function. Together with the frequency domain results, we present direct measurement of the group delay in time domain. Group delays from less than -300 ns to more than +300 ns were measured for a train of 3.3-μs wide sinusoidally modulated wave packet with carrier frequency at the first transmission minimum. This system is proposed as an alternative to active systems and photonic band-gap structures for sustaining both slow and fast light, with special emphasis in sensing purposes.

8425-61, Poster Session

Anomalous giant soliton formation near boundary of nonlinear layered PC and its propagation across the PC

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Among the various problems of laser pulse interaction with a photonic crystal (PC), soliton formation and light localization are very attractive problems because of their important applications in information technology, for example. In particular, propagation of soliton along the layers of PC is of interest. This propagation was analyzed recently in manu various papers on the basis of both Maxwell equations and Schrodinger equation and equation for a serious of discrete system. Light propagation in such structures was analyzed both experimentally and numerically as well. In this report we demonstrate a possibility of oscillating soliton formation near the boundary of nonlinear PC with ambient medium. It is very important that only a part of the soliton localizes in the PC. The other its part localizes near the boundary outside the PC. Hence, one can tell about the light energy localization at the lateral surface of the PC.

This soliton can propagate across the layers many times without leaving the PC. After its achievement of PC boundary soliton leaves partly the PC and then comes back in PC. Then soliton propagates to other boundary of PC. This process can repeat many times.

8425-62, Poster Session

Manifestation of spatial filtering performed by 3D photonic crystals

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We describe the usage of three-dimensional Photonic Crystals as spatial filters as an alternative method for improving spatial beam quality to conventional techniques. Furthermore we prove it experimentally. Photonic Crystal samples were manufactured by femtosecond laser pulses in a glass bulk (longitudinal and transverse periods were d(long) = 5.8 μm and d(transv) = 1.5 μm, the modulation of the index was of the order of 10^-3). The wavelengths we used for the experiment were 532nm (Nd:YAG laser) and 633nm (He-Ne laser).

8425-63, Poster Session

Tuning the properties of colloidal magneto-photonic crystals by controlled infiltration with superparamagnetic magnetite nanoparticles

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The quality of magnetic-field sensors and optical isolators is largely determined by the efficiency of the active materials. This efficiency could be dramatically increased by integrating Faraday materials in photonic crystals. For this purpose, monodisperse polystyrene nanospheres were self-assembled into a colloidal photonic crystal and magnetic functionality was introduced by repeatedly dipping the photonic crystal in a suspension containing superparamagnetic nanoparticles. Reflection measurements of these magneto-photonic crystals revealed clear relationships between the number of (mechanical) dips and the position and strength of the photonic band gap. When additional magnetic material was introduced, the band gap was redshifted and the strength of the band gap was decreased. Using Bragg's law and the Maxwell-Garnet approximation for effective media, the filling fraction of the magneto-photonic crystals was calculated from the observed redshift.

While superparamagnetic nanoparticles conferred magneto-optical properties to the photonic crystal, they also increased the absorption, which can be detrimental as the Faraday effect is measured in transmission. Therefore a trade-off exists in the optical regime between the amount of Faraday rotation and the absorption. By carefully controlling the filling fraction, this trade-off was investigated and optimized for photonic crystals with different band gaps. Furthermore, it was found that the maximum achievable filling fraction was influenced by the size of the polystyrene nanospheres. Smaller polystyrene nanospheres give rise to smaller pore diameters and a faster onset of pore blocking when filled with superparamagnetic nanoparticles. As a result, the maximum achievable filling fraction was also lower.

In this paper, an engineering approach is described to carefully control the filling fraction of magneto-photonic crystals. This allows fine-tuning the absorption and the position and strength of the photonic band gap. By tailoring the properties of magneto-photonic crystals, the means for application-specific designs and a better description of Faraday effects in 3D magneto-photonic crystals are provided.

8425-64, Poster Session

Group velocity control of reflected pulses in asymmetric Fabry-Perot filters

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Slow and fast light systems have attracted much interest in recent years because of their potential applications in communication networks. Whereas most of these studies deal with transmitted pulses, fewer results have been reported for reflected pulses. The issue of abnormal group velocities in pulse reflection is relevant in systems involving counter-propagating waves, such as in photonic band-gap structures (PBG), where the possibility of achieving group velocity control is particularly interesting for the development of optical delay lines. Recently, gain-controlled tuning from superluminal to subluminal group velocity was reported for pulses reflected in active fiber Bragg gratings. In this work we provide experimental evidence of group velocity tuning for pulses reflected in an entirely passive PBG system. The system is an asymmetric Fabry-Perot (FP) filter with Bragg mirrors, each one having different number of layers, for which we show that the group velocity can be tuned from subluminal to superluminal, and even negative values, by simply changing the spacing between the mirrors. These phenomena occurs for narrowband pulses with center frequency close to the reflection minima and it is associated to steep positive (slow light) or negative (fast light) slopes of the reflection phase function at these frequencies. Numerical and experimental evidence of group velocity tuning is provided. Experiments are performed in the radiofrequency range where the reflection phase function can be measured with a vector network analyzer. Also, group delays are directly measured in time domain by reflecting on these asymmetric FP filters a train of sinusoidally modulated wavepackets with carrier frequency in the MHz range. Our experimental results agree with theoretical predictions within the effective refractive index model. These asymmetric, linear and passive FP filters could be implemented in the optical range, and they are proposed as an alternative to active or non-linear media for group velocity control.

8425-65, Poster Session

A silicon photonic quasi-crystal structures obtained by interference lithography

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Photonic quasi-crystal structures have been prepared and investigated. Symmetrical patterns were fabricated by interference lithography in negative tone photoresist and transferred to silicon by reactive ion etching. Influences of symmetry and pattern details (depth of etching and constant lattice) on the reflection spectrum have been studied. Three types of 2D photonic quasi-crystals have been prepared: 8-fold, 10-fold and 12-fold pattern. Finally, finite-difference time-domain (FDTD) method was used for theoretically prediction of optical band diagram of fabricated quasi-crystals.

8425-66, Poster Session

Multiphonon acousto-optic interactions in normal and oblique incidence inside a 1D phoxonic cavity

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Creating a localized defect inside a phononic and photonic (phoxonic) structure allows to simultaneously localize sound and light on a scale of the order of the acoustic/optic wavelength. It is then possible to enhance their interaction through acousto-optic and opto-mechanical processes, and achieve mechanical control of light at the nanoscale. If a lot of both numerical and experimental work has been already realized in the Born approximation regime, few studies exist for multiphonon interactions. We use a method based on Green's function formalism in the frequency domain, and applied it both to normal and oblique incidence, extending results already obtained by Psarobas et al. [1] with their time domain approach. We show in particular that for a frequency near the localized optical mode, the phonon frequency cannot be neglected compared to the optical frequency in the simulation despite its small relative value, because the width of the optical mode starts to be comparable to the phonon frequency. Moreover, our first results on oblique incidence are as well presented. More specifically we explore the coupling between in- and out-of-plane polarized waves depending on the acoustic wave characteristics.

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8425-67, Poster Session

Dual phononic and photonic strip waveguides

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Many studies have been devoted to the search of photonic and phononic band gaps, but relatively few works are dealing with the simultaneous control of phonons and photons. Phoxonic structures hold promises for the simultaneous confinement and tailoring of sound and light waves with potential applications to acousto-optical devices and highly controllable photon-phonon interactions. The aim of this presentation is to investigate both the photonic and photonic band structures, and in particular dual photonic-photonic band gaps, in a model of silicon strip waveguide in which each unit cell contains one hole in the middle and two symmetric stubs on the side of the waveguide. We use the finite-element (FE) methods to calculate the dispersion curves and the finite difference time domain (FDTD) to obtain the transmission spectra.

Appropriate choices of the geometrical parameters allows us to obtain a complete phononic gap together with a photonic band gap of a given polarization and symmetry. Then, we investigate the possibility of confined modes inside cavities inserted in the phoxonic strip waveguide, which lead to an overlap of both elastic and electromagnetic fields. We also propose structures that can support simultaneously slow photonic and photonic branches. Both situations are suitable to enhance the photon-phonon interaction.

Finally, we discuss the actual values of the geometrical parameters, compatible with the technological fabrication constraints, in order to find the photonic features in the range of the telecommunication wavelengths, with the acoustic frequencies falling in the gigahertz regime.

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8425-68, Poster Session

Erbium doped two dimensional photonic crystals for band edge lasing

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In recent years, photonic crystal structures have become increasingly popular due to their unique optical properties. In particular, photonic crystal band edge lasers have shown continually improving performance. The enhancement of the optical density of states at a flat photonic band edge provides the optical feedback required for lasing. We report on the development of an Erbium doped two dimensional dielectric photonic crystal for enhanced directional emission.

Lanthanide metals provide an extended range of properties, including relatively long luminescence lifetimes and sharp absorption and emission bands. Recent work exploiting the properties of Erbium includes its use with rare earth doped fibers and photonic crystal structures. Embedding the dielectric matrix of the photonic crystal with Erbium ions provided a suitable optical gain medium to allow for an explorative analysis of the optical properties.

An initial computational study, using a direct frequency domain eigensolver and finite difference time domain simulations, was performed to optimise the band structure of the photonic crystal for optical performance. To achieve enhanced emission perpendicular to the photonic crystal surface, a flat band edge in the Gamma direction was required. In addition to optimisation, the simulations provided a theoretical comparison of the experimental results.

The development of both square and triangular based lattice designs, in addition to variations in the lattice constant and hole radius allowed for a detailed analysis of fabrication techniques and optical performance. Furthermore, a discussion of the possible applications is presented.

8425-69, Poster Session

Macroporous silicon photonic crystals as infrared selective thermal emitters

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In the last few years, photonic crystals have attracted much interest in the field of heat transfer engineering due to their unique optical properties of inhibiting spontaneous emission. Based on diffraction phenomena, the performance of a periodic modulation in the refractive index makes a given material to present spectral regions of allowed and forbidden frequency bands, the so-called modes and gaps. Such photonic band gaps define the spectral regions where thermal emission is suppressed, and their position and bandwidth can be controlled by the structure's morphological parameters. The fabrication of such optical structures, however, is still a challenging task most of all when three dimensionality is pretended. Macroporous silicon structures, consisting in an array of pores embedded in silicon whose diameter is periodically controlled in depth, have become good candidates to behave as three dimensional photonic crystals in the infrared.

In this work, macroporous silicon based photonic crystals are fabricated by electro-chemical etching of silicon. A prominent feature of that technique is that the periodicity of the structure in depth can be controlled independently from the surface pore distribution, allowing the fabrication of a great variety of optical structures.

Thermal radiation spectra of the emitters have been measured at high temperatures up to 1000 K by FTIR spectroscopy. Selective emission, due to the structuring, is clearly observed. Numerical calculations based on plane wave expansion method and transfer matrix method have been also performed to predict spectral properties of the emitters, allowing a previous design of the future fabricated structure.

Evaluations of selective emission shows that macroporous silicon selective emitters are effective to improve efficiencies of conventional thermal sources, which usually present a Lambertian radiation diagram and a plane distribution in frequency. The properties of macroporous silicon emitters should play an important role in the field of thermophotovoltaic energy conversion where it is desirable that only convertible photons reach the photovoltaic device.

8425-70, Poster Session

Slotted silicon hybrid microcavities for nonlinear applications

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Silicon nanobeam cavities consisting of two lines of equally spaced pores (Bragg mirrors) which enclose a straight section in a silicon strip waveguide gained recently renewed interest when several designs where developed allowing high Q-factors and relatively low mode volumina. With these properties the nanobeam cavities are of special interest for the enhancement of nonlinear optical processes e.g. optical bistability and opto-optical switching. However for efficient nonlinear processes in the near infrared the strong two photon absorption of silicon is a serious obstacle.

We therefore suggest a hybrid approach where a slot is introduced into the silicon nanobeam cavities. This slot can be infiltrated with other nonlinear optical materials (e.g. chalcogenide glasses) which experience the strong field enhancement within the slot, thus combining the efficient light confinement due to the high refractive index of silicon with the tailored nonlinear optical properties of the infiltrated material.

A theoretical investigation of the mode profiles, mode volumina and Q-factors of such infiltrated slot nanobeam cavities is presented. General design principles are discussed and in particular the impact of a gradual adjustment of the pore distance and pore diameter of the pores closest to the cavity is investigated. Especially the tapering of the pore diameter leads to a smoother transition of the mode profiles from the cavity centre to the adjacent Bragg mirror region resulting in a considerable increase of the Q-factors. Furthermore the influence of the length of the taper is considered and surprisingly a maximum Q-factor of 100.000 can be obtained with a linear taper including only two pores. Theoretical estimates predict that for such a filled cavity with a conservative Q-factor of 10.000 only a few mW of laser radiation would be necessary to observe optical bistability in form of a intensity dependent switching hysteresis.

8425-72, Poster Session

Design of an effective energy storage cavity in two-dimensional photonic crystal slab

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By adjusting the radii and positions of the lattice points in both parallel and perpendicular directions, we design a point-defect cavity in two-dimensional photonic crystal slab with excellent abilities in light confinement. Three-dimensional numerical analysis shows that discrete resonant modes have been found independently in each optical transmission band, starting from S to U band, with Q factor up to 40000 and light confinement up to 60%. Moreover, the light intensity is verified to suffer minor decrease of only -1.2 dB due to the insertion of a pair of w1 photonic crystal waveguides as the input and output access. All these features make our design a very promising candidate for light transmission and detection in practical applications.

8425-73, Poster Session

Resonant gratings based on electro-optic materials for tunable narrow-band optical filtering

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Based on the guided-mode resonance phenomenon, the refractive resonant grating has narrow-band and high reflectance peak in the spectra, which make it significant in filtering and telecommunication applications. In order to create a tunable filter, we studied the consequences of introducing electro-optic materials on the properties of the resonance peak. In this work, we propose a two-dimensional tunable resonant grating with a layer of electro-optic (E-O) material, and demonstrate the numerical results when an electric field is applied.

In general, the E-O materials' optical properties (tensor permittivity) change when they are subjected into an electric field. The LiNbO3 and BaTiO3 were chosen due to their strong electro-optical properties. We have chosen the orientation of each crystal in order to make sure the static electric field is applied in the direction corresponding to the greatest E-O coefficient rijk.

The structure is periodic in two orthogonal directions and the basic pattern is designed in order to increase the angular tolerance of the filter. When the electric field is applied, a peak displacement in the spectra is observed. In the case of LiNbO3, to achieve a shift of 11 nm, a 50V voltage is required, which leads to a too intense electric field (dielectric breakdown). In the case of BaTiO3, when 3V voltage is applied, it reaches a 6 nm displacement of the central wavelength of the refraction peak.

Nevertheless, together with the displacement of the peak, its properties as a function of the incident polarization are changed. Yet a polarization independent behavior is crucial for applications where the incident light is unpolarized or of unknown polarization. We aim to propose particular configurations for which the polarization independent behavior is retained when the electric field is applied.

8425-74, Poster Session

Fano resonances in Kagome fibers

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Hollow core Inhibited Coupling Fibers have been widely studied in recent years thanks to their ability to confine light inside the airy core. Only a small amount of mode power penetrates in the dielectric layers thus absorption and non linearity are greatly reduced. Kagome Fibers are the most investigated for applications spanning from THz to ultraviolet. Various studies have been devoted to the reduction of the confinement loss for these fibers, but most of them rely only on the optimization of the core-cladding interface. In this work confinement loss in kagome fibers are investigated by describing their microstructured cladding as an periodic arrangement of dielectric tubes with hexagonal shape. It is shown that spectral characteristics of the Kagome fibers can be described in terms of those of the single tube fibers which constitute the microstructured cladding. Unfortunately, the spectral characteristics of the hexagonal tube fibers are affected by Fano resonances between core modes and cladding modes. Such resonances affect kagome fiber characteristics too. Since circular tube fibers are free of Fano resonances, it is shown that fiber loss can be significantly reduces by making a microstructured cladding made of circular tubes instead of hexagonal ones. This will allow to provide general guide lines in the enhancement of confinement loss of microstructured fibers whose cladding is composed by an arrangement of tube waveguides of arbitrary shape.

8425-75, Poster Session

Elliptical hollow tube waveguides

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The development of waveguides for the Terahertz range is mainly limited by the high conduction losses of metals and the high absorption of dielectric materials. Hollow core Tube Fibers have recently been proposed as alternative solution to classical waveguides. Thanks to the inhibited coupling waveguiding mechanism the electromagnetic field is confined in the hollow core, thus greatly reducing the absorption from the dielectric material. In order to achieve low confinement loss for the guided modes, the core size is typically much larger than the wavelength. This cause these waveguides to be multimodal, but high order modes have higher confinement loss than the fundamental one. However, due to the rotational symmetry of the structure, the fundamental mode has two degenerate polarizations. Hollow core waveguides with rectangular cross sections have recently been proposed to destroy this degeneracy. Despite the very simple structure, it would be very difficult to carefully control the thickness of the rectangular tube during the manufacturing process. This holds especially for applications that require wide transmission bandwidths, i.e. very small dielectric thicknesses. On the contrary, elliptical tube waveguides break fundamental modes degeneracy and, at the same time, are easy to realize. These are investigated by starting from a circular tube by varying the ratio between major and minor ellipse semi-axes. Numerical results show that these fibers have very small birefringence even for high values of the ratio. Moreover, birefringence is highly frequency dependent: the maximum is reached at the borders of the transmission windows, while it is null at the center. On the other hand, confinement loss are higher for the fundamental mode polarized along the minor axis over the whole spectrum. This means that these fibers can not be used for polarization maintaining in broadband pulsed application, but as a polarization filter for randomly polarized sources.

8425-76, Poster Session

Numerical investigation of electrostriction forces in submicron phoxonic waveguide

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Nanostructured crystal waveguides have been investigated recently in view of obtaining simultaneous confinement of elastic and optical waves. Their interaction can be controlled by optical forces such as radiation pressure, which is predicted to scale to large values in nanoscale waveguides. Furthermore, Brillouin scattering is a nonlinear process where two photons generate a co-propagating acoustic phonon through electrostriction. This phenomenon is broadly documented for silica optical fibers, in both theory and experiment. Nevertheless, a general model including electrostriction forces is still needed to understand the optoacoustic interaction and to design ultra efficient optoacoustic devices.

In this paper, we perform numerical calculations of electrostriction forces for the Brillouin scattering phenomenon in different phoxonic submicron waveguides. After calculation of the optical guided modes of the waveguide by using the finite element method, the electrostriction-driven acoustic equation is solved for the displacement of the elastic wave by setting the acoustic wave vector and scanning the detuning frequency between the two optical waves. With this model, and according to the phase matching condition, we fully characterize Brillouin properties of phoxonic waveguides, including backward and forward Brillouin spectra, without the need to resort to a full band structure computation. To simulate realistic optoacoustic interaction conditions, elastic losses are incorporated in the electrostriction model by considering a complex elastic tensor.

We find that silicon waveguides seem to favor Brillouin scattering over silica waveguides. The combination of large relative permittivity and high simultaneous confinement of photons and phonons explains the computation result. To conclude, the calculation of electrostriction forces in phoxonic waveguides involves the simultaneous control of photons and acoustic phonons, thereby potentially improving the performance and overcoming some limits of current integrated devices.

8425-77, Poster Session

Optical induction of complex translation invariant photonic superstructures

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In the last decade photonic crystals have attracted considerable

attention due to their flexible possibilities of light manipulation by spatial variation of the refractive index. Periodic structures allow to control the spatial extent of light and are the basement of a variety of fascinating nonlinear effects that enable versatile steering and control possibilities as e.g. soliton formation, Zener tunneling, or Rabi and Bloch oscillations [1]. Consequently, different approaches were developed to design the refractive index of nonlinear media [2]. A new promising technique is the irradiation of a photorefractive medium by so-called nondiffracting beams which offer an invariant intensity distribution transverse to the propagation. These wave fields can be interpreted as superimposed monochromatic plane waves with a certain mutual phase relationship and commensurate longitudinal wave vector projections. A huge lineup of nondiffracting beams exhibiting a markedly enormous structural variety of transverse periodic and quasiperiodic patterning was discovered and experimentally implemented [3, 4]. Despite this multitude of variance - and also proper coherent superposition extend that lineup additionally - still there is a limitation of the structural variety, especially in terms of multiperiodicity. Furthermore, the investigation of arbitrary nondiffracting beams [5] does not yet provide a satisfying implementation due to a limited transverse resolution and an insufficient longitudinal stability of the intensity patterns.

In our contribution, we present a technique of incremental multiplexing (IMT) known from holographic data storage [6, 7] combined with nondiffracting lattice beams. This setup allows us to change the refractive index of a photosensitive material forming various translation invariant superstructures. Correspondingly, highly promising candidates for fascinating linear and nonlinear propagation effects like ratchet, rectangular or graphene superlattices were induced to show the possibilities of this method. In addition, IMT facilitates the induction of localized structures by adept separation of spatial frequencies. In connection with the induction of an optical lattice unique possibilities arise for the creation of defect sites in periodic lattice structures. For this approach a dynamic spatial frequency filter integrated in the setup allows for a flexible use of IMT. We utilize digital holography techniques to determine the induced refractive index change and to visualize the desired photonic structure. Our experiments show utmost convincing results regarding a succeeded induction and prove the high functionality and flexibility of our approach for the generation of complex multiperiodic lattices as well as localized or defect structures.

References

[1] Lederer et al., Phys. Rep. 463, 1 (2008)

[2] Elfremidis et al., Phys. Rev. E 66, 46602 (2002)

[3] Boguslawski et al., Phys. Rev. A 84, 13832 (2011)

[4] Becker et al., Opt. Express 19, 9848 (2011)

[5] Lopez-Aquayo et al., Phys. Rev. Lett. 105, 013902 (2010)

[6] Denz et al., Opt. Commun. 85, 171 (1991)

[7] Rose et al., J. Phys. D 41, 224004 (2008)

8425-78, Poster Session

Multiple Bragg diffraction effects in angle-resolved reflection and transmission spectra of opaline photonic crystal films

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We report on theoretical and experimental studies of multiple Bragg diffraction of light in three-dimensional photonic crystals possessing high dielectric contrast. Self-assembled opaline photonic crystals made up of monodisperse polystyrene microspheres are used as an example in our measurements. crucially new approach is considered to analyze and quantitatively describe the Bragg reflection and transmission complex-shaped contours. Our method is based on the dynamical diffraction theory generalized to the case of a three-dimensional spatially periodic medium characterized by high dielectric contrast and allows one to calculate in a simple analytical way the reflection and transmission spectra. The spatial Fourier components of the dielectric function are calculated taking into account a sintering of the spheres forming the opaline structure. Numerical calculations of the angle-resolved Bragg reflection and transmission spectra are performed, and those are compared with the dispersion curves of the electromagnetic eigenmodes for the opaline photonic crystals spatially confined along the [111] direction. The peculiarities in the optical spectra are found to correspond to singular points in the eigenmode dispersion curves. It is shown also that under the multiple Bragg diffraction conditions the reflection and transmission contours are shaped due to conventional photonic stop-band states as well as additional low-group-velocity modes ("slow light" modes). The contours calculated show a good agreement with our experimental data if a uniaxial strain along the sedimentation direction [111] and the particle sintering are accounted for. A possibility to observe the multiple Bragg diffraction effects at near-normal incidence of light is discussed for the opaline photonic crystals exposed to a strong uniaxial strain. We also predict theoretically the additional short-period interference pattern which is expected to arise for high-quality photonic crystal films in the resonant spectral range due to the "slow light" modes.

8425-80, Poster Session

Excitation of surface plasmon polaritons on sinusoidally corrugated metal-dielectric interface fabricated using interference lithography

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Using Finite-difference time-domain (FDTD) method, the excitation of surface plasmon polaritons (SPP) at the sinusoidally corrugated metal-dielectric interface was simulated. The sample structure was made by creating two-dimension sinusoidally corrugated dielectric layer on top of metal thin film deposited on dielectric substrate. The thickness of metal film was simulated in range from 10 to 100 nm. Both hexagonal and square symmetry was modelled with different grating pitch. The optical response of the structure was obtained in the regime of wavelength and angle. All simulations were performed for gold (Au) and copper (Cu) thin films deposited on glass substrate. Then selected structures were fabricated and measured. The metal film was thermally evaporated on glass substrate then the two-dimension sinusoidally corrugated dielectric layer was made in a photoresist using interference lithography.

8425-81, Poster Session

Design and modelling of photonic crystal superprism based on SRSN films for microspectrometer application with internal light source

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We propose a novel compact microspectrometer based on photonic crystal superprism with internal light source. Photonic crystal will be fabricated in Silicon-Rich Silicon Nitride (SRSN) layer that is known for its photoluminescence capabilities in a wide spectral range and high luminescence efficiency. Relatively high refractive index (2.0 - 2.8), good optical properties (e.g. high transmission in visible spectral range), well known manufacturing technology and possibility to integrate with electronic components on the same chip make silicon nitride an excellent candidate for photonic crystal engineering. A silicon quantum dots can be grown in a silicon nitride matrix by plasma enhanced chemical vapor deposition (PECVD) or magnetron sputtering. A two-dimensional photonic crystal superprism has been modelled using plane wave expansion (PWE) and finite difference time domain (FDTD) methods.

The equi-frequency surfaces (EFS) have been used to choose optimal parameters of photonic crystal which allows for wavelength separation of spectrum generated in SRSN layer. We considered a different lattice constants and hole radiuses of photonic crystal structures. Light propagation in superprism based on photonic crystal has been modelled using FDTD method. Based on these studies we suggested to implement designed structure into microspectrometer device which operates on the light generated by the photoluminescence phenomenon in SRSN films.

8425-82, Poster Session

Enhancement of negligible transmission band using hybrid periodic/Fibonacci one dimensional photonic crystal in near infrared and microwave domains

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The combination of periodic and quasi periodic one dimensional photonic band gap structures was the subject of many works. The approach has been generally explored to design resonant microcavities with strong mode localization or polychromatic filters. In this work, we propose to use this approach to enlarge the photonic band gap under grazing angles. We demonstrate the efficiency of the hybrid structure of the type Bragg mirror-(Fibonacci)S-Bragg mirror, with S is the repetition number of the Fibonacci block, to enhance the zero transmission band through the one dimensional photonic crystal in comparison with the periodic structure and the quasi periodic structure built according to the pattern of the Fibonacci sequence. We show that the maximum bandwidth to attain with the classic quarter wave periodic stack is limited and that the use of the Fibonacci sequence to stack layers of the photonic crystal permits to widen the band gap by increasing the generation number but the result is not very interesting because of the great number of layers. The efficiency of the hybrid configuration is proved in microwave domain and in the near infra red range. In microwave domain, we achieve under normal incidence a broad band which covers almost all the domain. The first proposed configuration is (LH)^8 [F_3 (1,1)] ^7 (LH)^8,so the total number of layers of this hybrid photonic structure is 53 layers. It permits to have a bandwidth of 34,7 GHz while with the periodic stack, the maximum bandwidth to attain is 17,22 GHz. The second revealed configuration is (LH)^8 [F_6 (2,2)] ^7 (LH)^8, it permits to have a bandwidth of 38,78 GHz which is an interesting result although the great number of layers. But, in microwave domain, the omnidirectional Photonic Band Gap exists only for angles below 57°. In the near infra red, the proposed design (LH)^8 [F_3 (1,1)] ^7 (LH)^8 exhibits a large photonic band gap at any angle of incidence under the two modes of polarization, Transverse Magnetic and Transverse Electric. The achieved omnidirectional photonic band gap has the width 0.858 µm while the periodic structure permits to have an omnidirectional bandwidth of only 0,2 µm. So the fulfilled omnidirectional bandwidth is larger than that of the periodic structure with an increasing ratio of 4.3 and also it covers all the optical telecommunication wavelengths 0.85, 1.3 and 1.55 µm. The proposed structure is a quarter wavelength mirror of only 53 layers. So, unlike the previous devices, the structure is simple to fabricate and it shows very interesting optical properties. To deepen the study, we investigate the sensitivity of the system optical response to the configuration parameters which are the repetition number S, the generation number of the Fibonacci sequence and the period's number of the two sidewall periodic stacks. The proposed system is a good candidate for the improvement of optoelectronic devices.

8425-83, Poster Session

Random laser emission in innovative structured optofluidic channel

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Random laser emission arises in mirrorless scattering active media when multiple scattering within the gain allows to overcome the losses. This field has gained popularity in the recent years due to its unique properties and ease of fabrication. The combination of optical devices with microfluidics has lead to the recent development of optofluidics. The properties of optical components such as lasers can be dynamically controlled with optofluidic channel (OfC) systems, which is not achievable with solid-state optical components. In addition, the development of OfC random lasers could open new avenues for sensing applications which require multidirectional lasers emitting single/multiple wavelengths. Here we report on the design of an innovative structured random lasing OfC. The origin of random lasing and various parameters affecting its properties are studied.

We have designed and fabricated a microfluidic channel with quasi-periodic structures along its length. When filled with an ethanolic dye solution and pumped by a stripe of laser beam, the inherent randomness in the structure of the quasi-periodic walls gives rise to the random lasing. Our studies affirm the need of a threshold pump stripe length and a threshold pump power to observe the random lasing effects.

8425-84, Poster Session

Random laser in totally disordered 2D GaAs/AlGaAs heterostructures

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Random lasing in active scattering media has raised tremendous interest since its first observation in 1999. An important feature of random lasers is that they are open systems with commonly strong leakage. In the regime of Anderson localization, random lasing action is easily explained in terms of well-localized modes inside the scattering medium. For instance random lasing has been recently reported in a semiconductor membrane, with a periodic array of holes. Fabrication imperfections provide with band-gap-edge localized states which can be selected by the gain. This regime is more difficult to reach in a completely disordered structure. Nevertheless, it has been shown theoretically that Anderson localization is not necessary and that random lasing can be achieved in the diffusive regime where modes are extended and strongly leaking.

We demonstrate experimentally for the first time random lasing in the diffusive regime on a semiconductor membrane with a fully-random collection of holes. Although modes are short-lived and leakage in the transverse direction due to the holes is high, the scattering process is sufficient to provide with enough feedback to trigger lasing action at reasonable optical pump density (~100kW/cm2). These results are obtained on fully-random patterns of subwavelength holes in a 2D $Al_{0.2}Ga_{0.8}As$ membrane with embedded GaAs quantum wells suspended on a low index $Al_{0.6}Ga_{0.4}As$ thick cladding. Laser operation is achieved under pulsed optical pumping. Several random patterns were tested and both single-mode and multimode emissions were observed. Comparing these results with spectrally-resolved diffusion measurement performed on the same samples, we confirm that lasing occurs in random patterns which exhibit diffusive behavior, away from Anderson localized regime.

8425-89, Poster Session

An overview of vanadates crystals used as laser materials

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Vanadate laser is usually used for lasers based on neodymium-doped vanadate crystals. In particular, these include yttrium vanadate (Nd:YVO4), gadolinium vanadate (Nd:GdVO4), and lutetium vanadate (Nd:LuVO4) which are also called orthovanadates. Such materials have been known for a long time , but became popular only many years later, because for a long period it was difficult to grow them with high optical quality in sufficiently large size. Apart from progress in crystal growth, the advent of diode pumping increased the interest in vanadates also because smaller crystals could be used.

Vanadate crystals are naturally birefringent, which eliminates thermally induced depolarization loss in high-power lasers. Also, the laser gain its strongly polarization dependent; the highest gain is usually achieved for polarization along the c axis.

The gadolinium vanadate (GdVO4) single crystal is an excellent laser host material with good laser properties, mechanical properties and chemical stability. The GdVO4 crystal doped with the rare earth has the luminous properties and has been proven as a kind of effective laser crystal with a low induced damage threshold.

Because of many applications of laser-diode pumped solid-state lasers, such as in the field of military, industry, medical treatment and scientific research, many studies were conducted on the LD pumped solid-state lasers and laser materials. In this field one of the famous laser crystal is Nd:YVO4, which has good laser properties and high chemical stability, and Nd:YVO4 crystal can also produce cw green laser at 0.53 μm when nonlinear crystals such as KTP or LiB5O5 (LBO) are used, the output power at 0.53 μm has been over 5W.A subgroup of intracavity Raman lasers are the self-Raman lasers, in which the laser crystal is also Raman-active. Self-Raman laser action in Q-switched devices for a variety of media the most promising are Nd:GdVO4, Nd:YVO4, Nd:PbMoO4 and Nd:KGd(WO4)2 .

8425-95, Poster Session

Inverted Yablonovite-like 3D photonic crystals fabricated by laser nanolithography

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No abstract available

8425-41, Session 10

High-Q (>600,000) photonic crystal nanocavities fabricated from chalcogenide glass fully embedded in an index matched cladding

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We have studied heterostructure cavities containing a W0.54 PhC waveguide fabricated from a chalcogenide glass film with index of 2.65 embedded in a material with an index equal to that of fused silica (1.45). In spite of the low index contrast a very strong resonant mode was found in this cavity. We calculated the Q-factor and effective mode volume of the mode at different cavity lengths with constant shift of 10nm, 6nm and 4nm respectively, and we found that the Q-factor can increase from 30,000~40,000 to 3,500,000 by simply increasing the length of cavity. The Q-values far exceed those which can be obtained in a W1 waveguide which are limited to ≈8000 Another positive result is that, even though the cavity is much longer than a traditional heterostructure cavity, the mode volume V, where Veff = V(λ/ncore)^3 can be controlled below 3 when the Q-factor is 1 million. We have fabricated sample structures using e-beam lithography from films of Ge11.5As24Se64.5 glass deposited on an oxidised silicon wafer. After dry etching the photonic crystal was coated with a liquid with an index matching that of fused silica to form the upper cladding. Experiments demonstrated intrinsic Q values of up to 650,000 were obtained and loaded Q values of ≈120,000. The embedded structure offers improved thermal management compared with a higher index contrast air clad waveguide. Experiments on optical switching in this high-Q cavity will be reported.

8425-42, Session 10

Group-III nitride 2D-PC microcavities integrated on silicon

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Group-III nitride semiconductors, namely (Al,Ga,In)-N and their alloys, have been shown to be excellent materials to fabricate efficient blue light emitting diodes and laser diodes [1,2]. However, many material issues and processing difficulties still remain to both, extend their emission range towards shorter and longer wavelength and to fabricate state of the art photonic devices. The main objective of this work is to fabricate group-III nitride 2D photonic crystal (2D-PC) microcavities for the realization of low threshold UV microlasers. Because of the chemical inertness of group-III nitrides, the fabrication of 2D-PC structures is difficult and quality factors (Q) achieved so far are quite low [3,4] compared to those obtained with other semiconductor materials [5].

By using (Al,Ga)N layers grown on silicon, an original bottom-up process is developed to fabricate 2D-PC cavities emitting at room temperature in the UV. The Si substrate is first nano-patterned by electron beam lithography and the PC pattern is then transferred by conformal epitaxy into the epitaxial AlN layer. Embedding GaN QDs in AlN epilayers provide efficient emitters up to room temperature in the UV range [6,7]. The Si substrate is then under-etched selectively and free-standing (Al,Ga)N-based 2D-PC cavities are fabricated. In this way, a modified L3 cavity exhibiting a Q of 1800 at 425 nm is demonstrated [8]. However, this bottom-up approach faces some difficulties and it turns out that the fabrication yield is quite poor. Recently, despite the inertness of group III-N materials, a classical top-down fabrication process involving e-beam lithography, ICP etching and a dry Si under-etching has been carried out on (Al,Ga)N layers grown on Si substrates. Following this fabrication approach state of the art Q values have been measured. The two approaches will be compared and fabrication of room temperature low threshold UV lasing integrated on silicon will be discussed.

[1] Yoshitaka Taniyasu1, Makoto Kasu1 & Toshiki Makimoto, Nature Letters, Vol 441, 325(2006)

[2] F. A. Ponce and D. P. Bour, Nature, Vol 386, 351 (1997)

[3] Y.-S. Choi, K. Hennessy, R. Sharma, E. Haberer, Y. Gao, S. P. DenBaars, S. Nakamura, E. L. Hu, and C. Meier, Appl. Phys. Lett. 87, 243101 (2005).

[4] M. Arita, S. Ishida, S. Kako, S. Iwamoto, and Y. Arakawa, Appl. Phys. Lett. 91, 051106 (2007).

[5] Bryan Ellis, Marie A. Mayer, Gary Shambat, Tomas Sarmiento, James Harris, Eugene E. Haller and Jelena Vuc˘kovic´, Nature Photonics, Vol 5, 297 (2011)

[6] S. Sergent, J.-C. Moreno, E. Frayssinet, S. Chenot, M. Leroux, and F. Semond, Appl. Phys. Express 2, 051003 (2009).

[7] S. Sergent, B. Damilano, T. Huault, J. Brault, M. Korytov, O. Tottereau, P. Vennéguès, M. Leroux, F. Semond, and J. Massies, J. Appl. Phys. 109,

053514 (2011).

[8] D. Néel, S. Sergent, M. Mexis, D. Sam-Giao, T. Guillet, C. Brimont, T. Bretagnon, F. Semond, B. Gayral, S. David, X. Checoury, P. Boucaud, Appl. Phys. Lett. 98, 261106 (2011).

8425-43, Session 10

Photonic crystal cavity definition by electron beam bleaching of chromophore doped polymer cladding

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Photonic crystal hetero structure cavities have attracted a lot of attention in the past few years. It has been shown that these cavities can exhibit very large Q-factors beyond 1e6 at still moderate modal volumes. Applications for this type of cavities include passive filters as well as electro-optic modulators and ultra compact lasers. However with the best processing technologies available today the attainable Q-factor is still limited by the resolution of the patterning process. State of the art electron beam facilities offer resolutions of about 1 nm. Simulations suggest that the Q-factor of such cavities could be increased significantly with increased resolution.

Since increasing the resolution of the structuring process is difficult we propose an alternative way to create high Q-cavities. We suggest to taylor the spatial Fourier spectrum of the cavity mode such that the fraction of the power spectrum at wave vectors within the light cone is minimized (k-space engineering). In order to achieve this we use a photonic crystal waveguide which is embedded into a chromophore doped polymer cladding and the refractive index of this polymer cladding is spatially tuned by electron beam bleaching with high spatial and refractive index resolutions.

As confirmed with experimental measurements on ring resonators with chromophore doped polymer cladding the refractive index change can be defined with a resolution of 1e-3. The change in refractive index yields a change in cut off frequency of the photonic crystal waveguide. The minimum refractive index change produces a frequency shift of the cut off frequency by only 0.05%. This change corresponds to a change in lattice constant of 0.21 nm which is not achievable with today's fabrication technologies.

It will be shown that the introduced refractive index changes can be tailored to achieve very smooth envelopes for the resonant mode inside the cavity. This reduces the vertical scattering and thus increases the intrinsic Q-factor. Simulations show that the intrinsic Q-factors of such arrangements can exceed 1e7. First results of heterostructure cavities bleached into photonic crystal waveguides will be also given.

8425-44, Session 10

3D optical micro-resonators by curving nanostructures using intrinsic stress

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It is emphasing that Micro-Nano-Photonics can be defined as the control of photons within the tiniest possible space during the longest possible time. Significant progress for quasi 3D control of photons has been achieved in our group along a 2.5D nanophotonics approach which can be considered as an extension of planar 2D photonic crystal-based technology exploiting the vertical direction[1,2].

We propose a new approach for the 3D control of light in real 3D optical micro-resonators that can be assimilated to 'cages', where photons are trapped efficiently[3]. The main attractive feature of this photon cages lies in their ability to result in a considerable enhancement of the electromagnetic field in the central part of the cage, that is in the air region, opening the way to new sensing or trapping of nanoparticles in fluidic (gas or liquid) ambiances.

Fabrication of three dimensional structures consists in exploiting the process of elastic relaxation of pattern formed in pre-stressed multi-layer structures[4]. The final shape of these objects can be predetermined by the distribution of the deformations in the various semiconductor layers, imposed during their epitaxial growth, before their freestanding from the substrate by selective etching.

We will present the basic concepts and fabrication we exploit to confine photons in air using cylindrical or spherical structures based on progressive relaxation of pre-stressed InGaP/InAsP bilayer films. It is worthwhile to notice that the formed microstructures exhibit patterns with dimensions compatible with optical operation in the visible/NIR wavelength range.

References

[1] X. Letartre et al, Journal of Lightwave Technology, 21, 1691 (2003).

[2] S. Boutami et al, Optics Express 15, 12443 (2007)

[2] C. Sieutat et al, Proceedings of SPIE Vol 7712 (2010)

[4] V.Y. Prinz et al., Physica E 6 828 (2000).

8425-45, Session 11

Photonic crystals with controlled deterministic aperiodic disorder

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Introducing disorder in a controlled way into photonic crystals allows studying the disorder-related change of the underlying transport mechanisms. Recently, controlled disorder has been introduced by mixing different ratios of spheres of different materials and assembling them into fcc opaline photonic crystals [1]. This leads to a random distribution of the defective sites.

Here, we introduce deterministic aperiodic disorder in woodpile photonic crystals. Deterministic aperiodic structures offer the possibility to reproducibly create specific potential landscapes whose Fourier components are determined by the underlying aperiodic sequence. In accordance with Lebesgue's spectral theorem the Fibonacci, Thue-Morse and Rudin-Shapiro sequences are examples of the three basic spectral measures, namely pure-point, singularly-continuous and absolutely-continuous, respectively. Especially, the Rudin-Shapiro series is said to be indiscernible from randomly disordered samples concerning their diffraction patterns/properties [2]. Varying the structural parameters, i.e., filling fraction and lattice spacing, according to the aperiodic sequences allows us to introduce deterministic aperiodic disorder into the photonic crystals.

Samples are fabricated via direct laser writing in negative-tone photoresist. After development the samples are characterized with transmittance and reflectance measurements as well as with Laue diffraction. The different types of aperiodic disorder can clearly be discerned in the Laue diagrams. Results from the samples with deterministic aperiodic disorder are compared to such from randomly disordered samples.

[1] P.D. Garcia et al., Phys. Rev. A 84, 023813 (2011)

[2] M. Baake and U. Grimm, J. Phys. Conf. Ser. 226, 012023 (2010)

8425-46, Session 11

Random lasers ensnared

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A random laser is formed by a haphazard assembly of nondescript optical scatters with optical gain. Multiple light scattering replaces the optical cavity of traditional lasers and the interplay between gain, scattering and size determines its unique properties. Random lasers studied till recently, consisted of irregularly shaped or polydisperse scatters, with some average scattering strength constant across the gain frequency band. Photonic glasses can sustain scattering resonances that can be placed in the gain window, since they are formed by monodisperse spheres [1]. The unique resonant scattering of this novel material allows to control the lasing colour via the diameter of the particles and their refractive index. Thus a random laser with a priori set lasing peak can be designed [2].

A special pumping scheme that enables to select the number of activated modes in a random laser, permits to prepare RLs in two distinct regimes by controlling directionality through the shape of the pump [3]. When pumping is essentially unidirectional, few (barely interacting) modes are turned on that show as sharp, uncorrelated peaks in the spectrum. By increasing angular span of the pump beams, many resonances intervene generating a smooth emission spectrum with a high degree of correlation, and shorter lifetime. These are signs of a phase-locking transition, in which phases are clamped together so that modes oscillate synchronously.

[1] R Sapienza, PD García, J Bertolotti, MD Martín, A Blanco, L Viña, C López, DS Wiersma, "Observation of Resonant Behavior in the Energy Velocity of Diffused Light" Phys. Rev. Lett. 99, 233902 (2007).

[2] S Gottardo, R Sapienza, PD García, A Blanco, DS Wiersma, and C López, "Resonance driven random lasing" Nature Photonics 2 (7), 429-432 (2008)

[3] M Leonetti, C Conti and C López, "The mode-locking transition in random lasers" Nature Photonics 5, 615-617 (2011)

8425-47, Session 11

Active control of the emission of a random laser

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With the rapid development of photonic-based new technologies, lasers of low dimensions are required. Designing laser cavities at the nanoscale is however challenging. Random lasers can provide with an alternative to this limitation. In a random laser, a concept proposed initially in the sixties by Lethokov, the optical cavity of the conventional laser is replaced by a scattering medium. When coupled to a gain medium, multiple scattering provides with the necessary feedback for lasing to occur. Since the first demonstration by H. Cao et al. in 1999 of lasing with coherent feedback in a cluster of ZnO nanoparticles, random lasers have been intensively studied. Fundamental questions have been addressed and possible applications have been proposed. One issue addressed recently is the impact of partial pumping on the lasing emission. Andreasen et al. have demonstrated recently that non-uniform pumping of the amplifying medium deeply changes the lasing spectrum. The emission spectrum remains however unpredictable. The question asked here is: "Could a random laser emission be controlled by adjusting the pumping of the gain medium?".

The solution proposed here is inspired from the recent demonstration of coherent control techniques applied to beam focusing through random media. Here, we propose an algorithm based on a simple optimization criterion to iteratively adjust the pump profile in order to select a particular lasing mode in the random spectrum. This algorithm has been successfully tested numerically. It is adapted in an actual experiment to drive a spatial light modulator, which modulates the pump impinging on an optofluidic 1D random laser.

8425-48, Session 11

Spatial control of second-harmonic light from a disordered structure

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Second-order nonlinear processes from crystals that are transparent but have a random structure of nonlinear domains can be efficient over a wide range of wavelengths without temperature or angular tuning. The emission direction of the nonlinearly generated light is determined by the typical domain size and shape. In the case of Strontium-Barium Niobate (SBN), in its most efficient configuration, the antiparallel-polarized needle-shaped domains emit the light distributed in a plane perpendicular to the long axis direction. At the same time, the intensity distribution is not smooth but forms a speckle pattern. This is something quite unusual for a transparent material with almost no change in the refractive index. We studied the characteristics of this speckle and compared with the usual one originated in diffusive materials.

A drawback of the nonlinear light generation in random materials is that the emission direction is quite broad and difficult to focus or collimate. Computer controlled spatial light modulators (SLM) have become a new tool to control the light transmitted through diffusive media. We have applied similar techniques to the nonlinear light generation in random but transparent crystals. We used a SLM to control the second-harmonic generation from a SBN crystal in the far field. We find that, in this way, light can be concentrated in a spot, nearly eliminating the rest of the speckle.

8426-01, Session 1

Preparation and characterisation of optical fiber tips for nanoscopic applications

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Silica-based, metal-coated as well as uncoated fiber tips are used in a variety of spectroscopic, micro-/ nanoscopic and optical sensor applications. The efficiency of such measurement systems is dependent on the tip geometry and the diameter of the tapered fiber end. In addition to taper drawing processes the tip shaping of the multimode standard-fibers is done primarily by wet-chemical etching usually in hydrofluoric acid. In the present study we investigated the preparation of geometrically predefined, nanoscaled fiber tips by utilisation of the dopant concentration profiles of highly doped step-index fibers. For this purpose, a gas phase etching process using hydrofluoric acid vapor was applied. The advantage of this approach is that all reaction products are obtained in a gaseous form and therefore surface condensation which often leads to etching inhomogeneities can be avoided. The shaping of the fiber tips base on very different etching rates depending on the etching treatment and doping characteristics of the optical fibers. Technological studies on the influence of the etching gas atmosphere on the time course of the tip shaping and the final geometry were performed on undoped silica fibers. The influence of the doping characteristics was investigated in phosphorus-, germanium-, fluorine- and boron-doped glass fibers. The etching behavior correlates with the doping-dependent refractive index profile of the fibers. Strong etching gradients take effect in the region of the central index-dip, since the dopant concentration is reduced to zero and therefore the etching rate is minimized. Narrow exposed as well as protected internal fiber tips in various shapes and tip radiuses down to less than 15 nm were achieved and geometrically and topologically characterized. For investigations on coating of planar surface plasmon resonance structures the fiber tips were coated with nanometer-sized silver layers by means of vapour deposition and finally subjected to an annealing treatment.

8426-02, Session 1

Investigation on colloidal Te doped CdSe (CdSe:Te) quantum dots suspension in a liquid-core fiber

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We demonstrate a double-clad fiber structure with a QDs suspension as active medium in the fiber core. The double clad fiber structure is achieved by inserting a Te doped CdSe-toluene suspension into the 25 µm hollow core of a silica capillary with a low index coating. To prevent the toluene suspension from changing the phase from liquid to gas and for stable long time conditions, we developed a technique to close and to seal both ends of the filled capillary. First of all we investigated the single pass photoluminescence in the region of the 632nm band of this double-clad fiber by excitation at 532nm. Later on we built up cavities with the goal of obtaining laser activity. We give an explanation why lasing is prevented in our case by intrinsic QDs mechanisms, e.g. Auger-recombination.

Quantum dots (QDs) or semiconductor nanocrystals (NCs) with a size comparable to or smaller than the exciton Bohr radius possess unique optical characteristics due to the quantum confinement. By reducing the size of the semiconductor bulk material below the exciton Bohr radius, the structure of the continuous valence and conduction band with a fixed energy bang gap changes to discrete atomic-like states with an energy band gap that is size depending. As the size of the QDs decreases, the band gap energy increases what is equivalent to a decrease of the absorption and emission wavelength. Since the band gap energy of the atomic-like states of the QDs depends on the quantum dot size, it is possible to tune the absorption and emission wavelength by controlling the size of the QDs, which can be easily realized by colloidal synthesis.

8426-03, Session 1

Formation of PDMS films inside the holes of silica photonic crystal fibers

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In this work, we demonstrate the formation of PDMS (Poly-dimethylsiloxane) films inside the holes of conventional silica photonic crystal fibers. PDMS elastomer is widely used in opto/microfluidics and soft lithography. It owns very good optical properties such as high transparency over a wide range of wavelengths, lower refractive index (around 1.41) than fused silica and negligible birefringence. It also exhibits very good mechanical properties due to low Young's modulus; it is soft and deformable with no shrinkage, it bonds relatively well to glass and it can be dissolved to many organic solvents. We prepared solutions of different concentrations of PDMS in hexane. The PDMS/hexane solutions were inserted inside the holes of the PCF using capillary forces. Over pressure up to 4 bars was used for more viscous solutions with higher PDMS concentrations. In a variant of the well-known dip-coating process, the PDMS solutions were moved inside the PCF holes with the aid of a pressure gradient. Films with thicknesses ranging from 100nm to 1.2µm were formed using different PDMS solution concentrations and different solution movement speeds. The thickness of films was very uniform along almost all the deposition length as indicated by SEM images. Due to the lower than silica refractive index of PDMS, light is guided purely by total internal reflection. Light transmission measurements from 400-1600nm were performed for all the structures. The index guiding properties of the new PDMS-layer/Silica structures were investigated and optimized numerically using FDTD analysis. The hybrid PDMS-layer/Silica structures retain to a large extend the advantages of both silica (regular structure, low loss) and polymer (bio-functionalization, thermal tunability, ease of doping) PCFs, hence making them very attractive for bio-sensing and other applications.

8426-04, Session 1

Optical temperature switch based on microstructured fibre filled with different chemical mixtures

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The size, shape and the location of the air holes allow for tailoring MSF parameters in a very wide range, way beyond the classical fibres, what opens up the possibilities for various applications. Additionally, the propagation parameters of MSF can be actively tuned when the air-holes are filled with different gases, liquids (e.g. liquid crystals) or solid materials (e.g. polymers). The mode confinement in such a filled MSF can be affected by the temperature dependent refractive index of the material filling the fibre. This idea puts forward a new type of components for creating novel fibre devices such as switches, attenuators and others.

Variable optical attenuators (VOAs) play an important role in optical communications as equalizers for dynamic channel power and

wavelength division multiplexing in a transmission system. Controlling and monitoring of optical power are also necessary in sensing applications, and especially, in optical systems which require high power laser operation or critical temperature threshold monitoring. Various types of VOA have been developed based on different mechanisms, such as bending loss control, light leaking from the fibre cladding, temperature tuning of the polymer incorporated into the tapered microstructured fibre or electrical tuning of the liquid crystal layers.

In this paper we would like to discuss the highly dynamic VOA based on a tuneable microstructured fibre filed with different chemical mixtures used as an on/off temperature switch. Furthermore, a technology of low loss coupling and splicing of the applied MSF with standard single mode fibre has been developed. Therefore in the proposed application the optical signal can be transmitted to and from the switch by standard telecom fibre, which considerably reduces transmission losses and allows usage of standard off-the-shelf components reducing costs of the overall system.

8426-05, Session 1

Microstructure-assisted grating inscription in photonic crystal fibers

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Fiber Bragg gratings are one of the most important elements of fiber technologies and found applications ranging from optical communication to all-fiber lasers. One of the recent methods of grating inscription is based on inducing an array of highly localized index changes in the silica core of a fiber by tightly focused high intensity laser pulses. There were already several reports of such point-by-point gratings in conventional step index fibers. Applying this technique to photonic crystal fibers is still not straightforward. The main reason is the air holed microstructure which distorts the wave front of the inscribing laser beam and counters the focusing of the light in the core.

We propose a new concept of microstructure-assisted grating inscription in photonic crystal fibers by introducing a focusing microstructure in the cladding of the fiber. We designed special types of photonic crystal fibers with a photonic crystal Mikaelian lens (PCML) in their cladding. Such a PCML is the implementation of a conventional Mikaelian or gradient index lens in a photonic crystal lattice. The effective index variation in a PCML is achieved via a variable air hole radius. In a fiber that is foreseen of a PCML the inscribing laser beam can be tightly focused to the fiber core. This concept allows to increase optical power densities in the core of PCF by an order of magnitude. We present a numerical model of a photonic crystal fiber with a PCML designed for 800 nm wavelength 125 femtosecond laser pulses.

8426-06, Session 1

Photonic bandgap guiding into a composite AgPO3-glass/silica microstructured optical fibre

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Infiltration of soft glass matrices inside Photonic Crystals Fibres (PCFs) for achieving photonic band-gap (PBG) guidance and expand device development capabilities has been recently demonstrated. Herein, we report the fabrication of an all-solid PBG guiding PCF by suction-assisted infiltration of molten silver-metaphosphate (AgPO3) glass into the micron diameter capillaries of a commercial PCF. The incorporation of AgPO3 glass inside the capillaries of a solid core PCF can constitute a strong base for the development of new sensing and scattering in-fibre devices, by exploiting the high photosensitivity of silver and its specific plasmon absorption properties. The PCF infiltrated was the LMA10 with air capillary diameters of 2.9 m, manufactured by Crystal Fibre. The AgPO3 glass was melted from powder components. Such glass exhibits a low glass transition temperature of ~190°C. The relatively low viscosity of the AgPO3 glass melt allowed infiltration at ~700°C inside an annealing oven apparatus by applying suction with the use of a standard mechanical vacuum pump. A few centimetres of LMA10 fibre that was glass-infiltrated within 0.5cm long section was characterised by means of its transmission spectrum by employing a supercontinuum source coupled into the PCF using optical objective setup. The measured transmission spectra of this fibre demonstrated a strong bandgap guiding effect over the measurement range (400-1750nm) with signal attenuation of 40-60dB/cm in the spectral stopbands despite the low refractive index contrast (~0.22) of the cladding microstructure. Eight transmission bands were observed within the spectral range of 400-1750nm. Numerical simulation of the expected transmission spectra, calculated by Beam Propagation Method (BPM) and Anti-resonant Reflecting Optical Wavelength model (ARROW), are in progress for confirming the experimental data. Results on reducing the transmission losses and tuning of the bands spectral allocation will be presented on-site.

8426-07, Session 2

A smart-skin shear sensor based on ferrofluid infiltrated Bragg grating in a microstructured optical fibre

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Lately there is an increasing demand for accurate and of high dynamic range shear sensors, mainly triggered by the rehabilitation, security and sensitive goods transportation sectors. Herein, we demonstrate a compact, flexible and high dynamic range optical fibre shear sensor based on an embedded, microstructured optical fiber (MOF) Bragg grating infiltrated using ferrofluid in a Polydimethylsiloxane (PDMS) block, constituting a “smart skin shear sensing pad”. A small volume of a hydrocarbon ferrofluid was infiltrated in a grape-fruit type MOF in which a 22mm long, Bragg grating was previously inscribed using 193nm laser radiation. The short ferrofluidic medium length (~2mm) compared to the length of the grating, acts as a phase defect forming a lossy Fabry-Perot cavity, by dividing the grating into three interacting segments. As a result a dip is formed in the reflection grating spectra, its position and strength depending on the position of the ferrofluid along the grating. This ferrofluidic infiltrated MOF Bragg grating was embedded into a 30×20×5mm PDMS elastic block, being aligned along its long axis and positioned close to the top surface of the block. A small size, spherical magnet, having 1.5Kgauss strength was fixed inside the PDMS block at suitable position with respect to the grating and the ferrofluidic defect, forming the magnetic stimulus. Shear stress applied at the top surface of this “smart skin” resulted in a relative displacement of the ferrofluid controlled by the magnet, along the Bragg grating length. This displacement was manifested as a clear change in the strength of the spectral notch, measured in reflection mode. Fully repeatable shear displacements of the “smart skin” from 250 m to 4.5mm were monitored, corresponding to spectral changes of 4.5dB in maximum. Shear sensing results will be presented for different grating and ferrofluid lengths, while being correlated to the shear stress parameters of the PDMS skin.

8426-08, Session 2

Optical RI sensor based on an in-fiber Bragg grating Fabry-Perot cavity embedded with a micro-channel

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Optical fiber based reflective index (RI) sensors are widely applied in chemical/biomedical measurement and environmental monitoring applications, due to their desirable characteristics, such as small size, high sensitivity, immunity to electromagnetic interference and safe-operation for hazardous environmental conditions. Most fiber grating based sensors achieved the RI sensing by evanesce field coupling, which is an indirect method, and the sensing response to RI is not just nonlinear but also with a very narrow sensing range limited from 1.4 to 1.44. Extrinsic Fabry-Perot (F-P) interferometers have good linear response to the RI of the cavity and thereby the surrounding medium, but Intrinsic F-Ps, suac as in-fiber Bragg grating F-P structures, are insensitive to the surrounding medium, because the light coupling is confined within the core modes. With the development of femtosencond laser micromachining technique, it is possible to create a micro-channel in the cavity of the in-fiber Bragg grating F-P, inducing a mechanism for route of light interaction with surrounding medium. Such a structure thus can be implemented as an RI sensor.

In this paper, we report a linear response optical RI sensor, which is fabricated by creating a micro-channel in the cavity of an in-fibre Bragg grating F-P using femtosecond laser inscription and chemical etching. The experimental results show the F-P resonance peak has a linear response with the RI of surrounding medium and the RI sensitivity is proportional to the width of micro-channel. The sensor with 5 μm-wide micro-channel exhibited an RI sensitivity of 1.15nm/RIU and the sensitivity increased to 9.08nm/RIU when the micro-channel widened to 35μm. Furthermore, such micro-channel FP sensors show a much broader RI sensing dynamic range, as for 5 μm-wide micro-channel device, the sensing range is from 1.3 to 1.7, which is much broader than from 1.4 to 1.44 of reported fibre grating based RI sensors.

8426-09, Session 2

Design of turn-around-point long-period gratings in Ge-doped photonic crystal fibers for evanescent sensing

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The numerically optimized Ge-doped photonic crystal fiber long-period gratings operate around the dispersion turning point on the phase matching curve of the coupled modes. This special type of LPG, referred to as a Turn-Around-Point (TAP) LPG, can be employed for evanescent broadband absorption spectroscopy or optical intensity-based refractometry. The numerical optimization of a PCF-LPG utilizes the finite element method for PCF modal analysis and the simplex downhill method to minimize the objective function based on target-specific PCF properties. For gas and aqueous analytes infiltrated into PCF's air holes, the TAP PCF-LPG's periods are shorter than those achievable with a CO_2 laser LPG inscription, and therefore the use of a femtosecond laser is supposed. The transmission spectrum of a TAP PCF-LPG is highly sensitive to variations in PCF geometrical parameters. The performed numerical simulations show that possible adverse effects of imprecision in PCF fabrication on the LPG's transmission spectra can be mitigated with a strong refractive index modulation, which can be achieved easier in a Ge-doped PCF than in a pure-silica PCF. Moreover, germanium doping allows to precisely define the grating area for maximizing the coupling coefficient. Potential and limitations of TAP LPGs inscribed with a femtosecond laser into Ge-doped PCFs for evanescent chemical and biochemical sensing will be evaluated.

8426-10, Session 2

In-fiber temperature measurement during optical pumping of Yb-doped laser fibers

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The knowledge of temperature effects in rare-earth doped fibers is of great interest in order to improve the performance and stability of monolithic fiber lasers and fiber amplifiers. Fiber Bragg gratings (FBGs) are, in general, well applicable to measure local temperatures within an optical fiber.

We report on the inscription of FBGs in rare earth doped optical fibers, the reduction of inherent absorption effects in the FBGs and the FBG-based temperature measurement within the core of actively doped fiber samples during core pumping.

Experiments were performed on fibers with standard geometry (125μm cladding, 8-10μm core diameter) and different Yb content but comparable P and Al composition. The FBGs were inscribed using UV-femtosecond pulses and a modified Talbot-Interferometer. A Bragg reflection wavelength at 1550 nm far from the Yb-fluorescence spectrum was chosen for the temperature measurements. Short fiber samples (1cm) with the inscribed FBGs were investigated for different cooling conditions with air or water cooling. Temperature changes have been measured depending on the Yb content under high inversion and depending on the time including the photodarkening kinetics of the fiber. The experiments have shown that FBGs can be a useful tool for the investigation of temperature within actively doped optical fibers and might also be applicable for spatial distributed temperature measurements during fiber laser operation and for inversion detection.

8426-11, Session 2

An FBG based hydrostatic pressure sensor for liquid level measurements

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A small and simple hydrostatic pressure sensor based on fiber Bragg grating and a stainless steel cylinder partially filled with silicone rubber is reported for liquid level sensing in downhole application. The working principle of the sensor head design is based on transferring hydrostatic radial pressure to axial strain to the FBG. A FBG having reduced diameter of 50μm has been used for the measurement. The experimental result shows that sensitivity can reach 23pm/cm of liquid column. For simultaneous measurement of liquid level and its temperature, one more FBG is used. The results show high sensitivity, good linearity of the response of the sensor. The small size and rigid structure of the encapsulated sensor head can be useful to measure liquid levels in downhole applications.

8426-12, Session 3

Fibre Bragg gratings written in highly birefringent microstructured fibre as very sensitive strain sensors

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The possibility of manufacturing highly birefringent (HB) microstructured fibres (MSF) made these fibre types very attractive for use in sensing applications. In contrary to traditional optical fibre sensors, properly designed MSF based components do not need temperature compensation as their birefringence remains insensitive to temperature changes. In our paper we show that HB MSFs with Fibre Bragg Gratings (FBGs) written in the fibre core region can be successfully used as very sensitive strain transducers. The Bragg wavelength can be given as a function of strain, hence the changes in fibre strain can be calculated from the changes in the difference of Bragg wavelength peeks of the two orthogonal polarization modes. For that reason the presented experimental set up does not use any complex polarization analysis equipment, but simple optical spectrometer which can be easily located at a distance from the sensor itself. Furthermore a technology of low loss coupling and splicing of the designed HB MSF with standard SMF-28 has been developed. Therefore in the proposed application the measured signal can be transmitted to and from the sensor by standard telecom fibre, which considerably reduces transmission losses and allows usage of standard off-the-shelf components reducing costs of the overall system, Our research results show that the strain sensitivity significantly increases, two orders of magnitude compared with classical fibre sensors, for the second order mode, while the temperature sensitivity remains relatively low, therefore strain remains easily distinguishable from temperature changes. The proposed strain sensors can be easily combined in multiple arrays with the signals multiplexed in SMF-28 fibers, which gives an interesting perspective for application in complex commercial environments.

8426-13, Session 3

A grating-less in-fibre magnetometer realised in a polymer-MOF infiltrated using ferrofluid

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We present a simple grating-less, in-fibre magnetometer realised in a PMMA-microstructured optical fibre that has been infiltrated using an oil based ferrofluid. This fibre based magnetometer operates in transmission mode. The fibre used is a single-mode microstructured polymer optical fibre with the hexagonal hole arrangement typical of such fibres. The ferrofluid infiltrated is fabricated from Ferrotec, and diluted using isoparaffinic solvent for reaching a concentration below 20% and a refractive index of the order of 1.45. The length of the ferrofluid infiltrated into the fibre is ~1cm approximately. Unpolarised, fibre-to-fibre, broadband spectral measurements performed covering a typical spectral window from 500nm to 1100nnm, revealed that the infiltration of the lossy ferrofluid into the fibre microstructured results in the generation of a short cut-off band located at the vicinity of 600nm. By applying magnetic field perpendicular to the fibre axis, the specific cut-off band shifts to longer wavelengths, exhibiting a dynamic behaviour with respect to the magnetic field applied; the rest of the spectrum above 700nm remains almost unaffected. Typical spectral cut-off shifts are ~45nm for a magnetic field of 1KGauss, resulting in extinction ratio changes of 8dB at 613nm. The infiltrated magnetometric fibre exhibits polarisation sensitivity upon the application of the magnetic field with respect to the rotational symmetry the fibre axis, providing the possibility of directional measurements. Preliminary measurements show that the polarisation sensitivity of the device is greater than 3dB at 633nm. Additional experimental data related to the chromatic and modal tuneability of device, the directional sensitivity and simulations of its modal properties will be presented on-site. An analysis on the physical background of the ferrofluidic optical tuneability will also be presented.

8426-14, Session 3

Curvature sensor using a photonic crystal fiber with three coupled cores

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A curvature sensor using a Photonic Crystal Fiber (PCF) with three coupled cores was proposed. The three cores are aligned and had two small air holes between them which act as defects. Due to the relative positions of the cores, an interference pattern is obtained between them. The sensing head had 0,13 m of PCF and the configuration used in this experience was interrogated in reflection with a cleaved fiber ending. When the fiber is bended, one of the lateral cores will be stretched and the other compressed. This changes the interaction pattern between the three cores, changing the optical power intensity. The sensibility of the sensing head was strongly dependent on the direction of bending, having its maximum when the bending direction was along the plane of the cores and its minimum when the bending direction was perpendicular to the plane of the cores. A minimum sensitivity of -0,62 dB.m, and maximum sensitivity of -1,63 dB.m was demonstrated. It was verified that the optical intensity variations with the temperature were below our measurement resolution. Also, a low temperature sensitivity of the peak wavelengths is expected for PCFs.

8426-15, Session 3

Strain characterization of suspended-core fiber tapers

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In this work, a spatial optical filter based on a hollow core silica tube is presented. Due to the core dimensions, it is possible to obtain a periodical spatial filter ranging from 1200 to 1700 nm with a wavelength peaks separation of 13 nm. The bandwidth is approximately 5 nm, and the isolation loss of 30 dB. The optical losses are of approximately 4.5 dB/cm. Different spatial optical filters were made, by using different lengths and all the spectra obtained were identical. Therefore, the behavior of the spatial optical filter is independent of the length. The 40 mm long spatial optical filter was tested as a sensing element, and subjected to different physical parameters. When the longitudinal strain and temperature are applied, the spatial filter is wavelength sensitive. However, when the sensing head is immersed in different refractive index liquids the optical power decreases. The sensing head is also characterized in axial strain, evidencing insensitivity to this parameter. This sensing head can be used for extreme conditions, as high temperatures, where it presents a sensitivity of 0.02 pm/°C.

8426-16, Session 3

Low power and inexpensive microstructured fiber Mach Zehnder interferometer as temperature insensitive mechanical sensor

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Microstructured fibres (MSFs) reveal unique properties including endlessly single-mode operation from ultraviolet to infrared wavelengths, very high birefringence or nonlinearity, very large or very small effective mode field area, and many others. The size, shape and the location of the air holes allow for tailoring MSF parameters in a very wide range, way beyond the classical fibres, what opens up the possibilities for various applications. Due to their advantages MSFs obtain growing attention for their perspectives in sensing applications. Different MSF sensors

have already been investigated, including interferometric transducers for diverse physical parameters. Until now, there have not been any publications reporting on the sensing applications of MSF Mach-Zehnder interferometers, targeting the mechanical measurements of vibrations, dynamic or static pressure, strain, bending and lateral force.

Moreover, a critical feature opening the prospective of optical fibre transducer to successfully accomplish a particular sensing task remains its cross-sensitivity to temperature. Studied MSF is made of pure silica glass in the entire cross-section with a hexagonal structure of the holes. Consequently, there is no thermal stress induced by the difference in thermal expansion coefficients between the doped core region and the pure silica glass cladding, in contrast to standard fibres.

In this paper we present the experimental comparison of mechanical and temperature sensitivities of Mach-Zehnder interferometer with replaceable FC connectorized sensing fibre arm, such as: off-the-shelf endlessly single mode MSF or standard telecom single mode fibre. Experimental results clearly show very low cross-sensitivity to temperature of studied MSF compared with standard fibre. Additionally, microstructured fibre Mach-Zehnder interferometer with standard FC receptacles allows using different fibres as sensors with the same device. Moreover, investigated interferometer consumes in total extremely low electric power (< 20 mW) due to the implementation of exceptionally effective data analysis electronics and VCSEL as the light source.

8426-17, Session 4

Active material for fiber core made by powder-in-tube method: subsequent homogenization by means of stack-and-draw technique

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Modified Chemical Vapor Deposition (MCVD) technique is now the main method of fabrication of preforms for active optical fibers. However, in case of doping by rare-earth ions this method has certain limitation. In particular, there are radial variations in refractive index of the core made by MCVD method which can prevent high-quality beam propagation in large-mode-area fibers.

Powder-in-tube (or granulated oxides) technique [1,2] is an interesting alternative to the MCVD one. In this case, silica tube is filled with a mixture of powders of oxides (for example, silica, aluminum oxide, ytterbium oxide) which is followed by fusion at glass-working lathe or during fiber drawing. A serious drawback of this method is a relatively strong s att ring the fibers produced which originate from insufficient mixing of the components: time and temperature of the process are insufficient for good homogenization. Thus, improving the homogeneity is a critical issue for this method.

In this presentation we investigate the possibilities to improve homogeneity of the fused material by means of subsequent stack-and draw procedures. The decrease of scattering-related optical losses in optical fibers observed after each cycle of stacking and drawing will be compared with the evaluations of homogeneity made from AFM pictures of etched fiber end-faces. A total loss decrease from 300 to 60 dB/ km for Al-doped fibers will be demonstrated.

References

1. Ballato J., Snitzer E. - Fabrication of Fibers with High Rare-Earth Concentrations for Faraday Isolator Applications. - Applied Optics, 34(30), 6848-6854 (1995).

2. M. Neff, V. Romano, W. Luthy. - Metal-doped fibres for broadband emission: Fabrication with granulated oxides. - Optical Materials, 31 (2), 247-251 (2008)

8426-18, Session 4

Flattened fundamental mode in microstructured optical fibers: design and realization

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Fiber lasers are entering the market of high-power systems for many applications due to their high beam quality, compactness, reliability and stability when compared to bulk systems. In some applications such as high-power amplification or micro-machining, performances should be increased by shaping the spatial intensity distribution of the optical beam so as to obtain a flat-top intensity profile. Usually, this is achieved by using massive optics such as phase plates, focusing elements or costly deformable mirrors. However, these solutions are not compatible with the all-fiber geometry that is expected for an easy use of fiber laser system.

In this talk, we will present the design and the realization of a passive air/silica microstructured optical fiber that delivers a flat-top intensity profile. To reach this goal, we have revisited the well-known concept, in which a flat-top intensity profile can be achieved by using a cylindrical core surrounded by a thin ring constituted of high refractive index material. In the present work, a special care has been paid to develop a design that is realistic and compatible with an experimental realization. Moreover, the proposed design can be realized by using the “stack and draw” technique and supports only a few modes. General design rules established from intensive numerical simulations will be presented during the conference. Precisely, we will show how to find the best geometry with an optimization process and how the root-mean-square variations of the intensity profile compared to a flat-top one depend on index profile and geometry parameters. Bending sensibility of losses and modal dispersion will be also numerically evaluated. Finally we will present the experimental demonstration of a fiber presenting a flat-top intensity profile at a wavelength of 1.05 µm with an effective area larger than 350 µm^2.

8426-19, Session 4

The influence of the drawing process on the intrinsic stress in optical fibers and the arising possibility to optimize the birefringence of PM fibers

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The properties of optical fibers can significantly be influenced by intrinsic stress. It is well known that these stresses are caused by various reasons, e.g. the variations in the thermal expansion coefficient (CTE) of the differently doped regions in the fiber. The so called thermal stresses are only dependent on the composition of the fiber and not on its preparation history. One other main reason for stress in the final fiber is the mechanical force that is applied during the drawing process of the fiber. It generates so called mechanical stresses that depend on the composition of the fiber and the thermal history the fiber passed through.

To differentiate between these two kinds of stress it is necessary to measure on the one hand the thermal induced stresses in the preform of a fiber. On the other hand, we measure the final stress state in the fiber. Knowing both, it is possible to conclude on the stress that is induced by the process of fiber drawing.

Using a non-destructive polarimetric system, we are able to measure the intrinsic stress state in optical fibers as well as in their preforms. We can show that the applied force during the fiber drawing significantly influences the stress in the fiber. We find that for high drawing forces, the stress state can be turned upside down in comparison to the thermal stresses that are induced by the material composition.

Due to the fact that stress on the one hand has a strong effect on the mechanical properties of glass and modifies the refractive index, this can lead to significant effects on the fiber stability and modal behaviour. For example, we will show how different mechanical stress states in polarization maintaining fibers influence their birefringence.

8426-20, Session 4

Erbium doped low phonon glasses for application in up-conversion fiber lasers

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Despite significant progress in development of wide bandgap semiconductors observed in the past years, dielectric media, specifically those offering possibility of obtaining short wavelength lasing under infrared pumping, are still considered as a promising solution in all applications requiring lasing parameters not available for laser diodes. Solid state lasers, specifically in fiber geometry, are constantly considered as irreplaceable in all applications requiring excellent optical quality of the beam together with high power levels. What is more, they may offer light emission and lasing in spectral ranges not available to typical semiconductor lasers.

Among various rare earth ions, employed in solid state laser systems, trivalent erbium seems to be one of the most attractive, due to its rich energy level structure enabling several laser channels in the infra-red and visible part of spectrum, including the most demanded green lasing. The green lasing has been already reported for several up-conversion pumped crystalline materials as well as active fluoride fibers. Nevertheless, the up-conversion phenomena and lasing potential of tellurite glasses still remain not fully explored.

In this work we present the results of our studies on up-conversion phenomena in erbium doped tellurite TZN glasses (with chemical composition 78TeO2-11ZnO-11Na2O) compared with the results obtained for fluorozirconate ZBLAN glasses (with composition 53ZrF4-20BaF2-4LaF3-3AlF3-20NaF). The two sets of bulk samples of these glasses, differing in concentrations of active ions, have been investigated with specific attention focused on analysis of up-conversion processes resulting in short-wavelength emission under infrared (808 nm, 980 nm, 1480 nm) and red (657 nm) pumping by commercially available semiconductor lasers diodes. In particular, absorption characteristics were measured at room and cryogenic temperatures, followed by measurements of fluorescence dynamics profiles of excited levels and emission characteristics obtained under both single-photon and multi-photon excitation. As a result the main spectroscopic parameters were determined, including ground and excited state absorption cross sections, emission cross sections as well as fluorescence lifetimes. The possible up-conversion pathways were identified and carefully analyzed, giving a good starting point for optimization of tellurite glass composition, active dopant levels and excitation conditions, which, in turn, enabled technological attempts to fiber drawing. Finally, the set of telluride fibers doped with 10000 ppm of erbium ions, differing in core diameters was manufactured in the Institute of Electronic Materials Technology and characterized with respect of up-converted emission and lasing properties in the visible spectral range under up-converted pumping. The results were then compared with these reported for erbium doped ZBLAN fibers.

8426-21, Session 4

Optical properties of Bi-doped Mg-Al-silicate glasses and fibers

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The paper compares the absorption and emission properties of bulk glasses sintered in an iridium crucible and of optical fibers fabricated by “powder-in-tube” technology. Both bulk glasses and fibers were prepared from identical charges. The emission properties of bulk samples and fibers were close while the “grey losses” in the fibers were an order of magnitude lower than those in bulk glasses melted in an iridium crucible.

8426-22, Session 5

Spectral interferometry-based dispersion characterization of microstructured and specialty optical fibers using a supercontinuum source

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In this paper, we present two spectral interferometric techniques employing a supercontinuum source for dispersion characterization of birefringent microstructured [1] and specialty optical fibers [2] over a broad spectral range (e.g. 500-1600 nm). First, a technique employing an unbalanced Mach-Zehnder interferometer [1, 2] with a supercontinuum source is used for measuring the chromatic dispersion and zero-dispersion wavelength of the one of the polarization modes supported by a microstructured optical fiber. Second, a technique employing a supercontinuum source with a tandem configuration of a Michelson interferometer and a fiber under test [2, 3] is used for measuring the group modal birefringence in the fiber. From these measurements, the chromatic dispersion and zero-dispersion wavelength of the other polarization mode supported by the microstructured optical fiber are retrieved. We also measured by the second technique the chromatic-dispersion difference as a function of wavelength and its zero value wavelength for an elliptical-core optical fiber. We revealed the dependence of zero-dispersion wavelength on the geometry of a pure-silica microstructured optical fiber. Similarly, we revealed that the zero chromatic-dispersion difference of an elliptical-core optical fiber can be tuned by the fiber geometry and fiber glass composition.

[1] P. Hlubina, et al., Opt. Express, 15, 11073-11081 (2007).

[2] P. Hlubina, D. Ciprian, M. Kadulová, Meas. Sci. Technol., 21, 045302 (2010).

[3] P. Hlubina, D. Ciprian, M. Kadulová, Meas. Sci. Technol., 20, 025301 (2009).

8426-23, Session 5

Investigation of dispersion characteristics of highly nonlinear microstructured fibre series for customized supercontinuum generation

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Dispersion characteristics are the fundamental properties of microstructured fibres (MSFs) with respect to the nonlinear applications. MSFs can be designed with very diverse dispersion characteristics. The changes of fibre dispersion may strongly influence the whole chain of diverse nonlinear effects resulting in supercontinuum generation (SG). Transferring the experience from the topics related to tailoring different properties of MSFs to investigate the potential design freedom of

dispersion opens novel possibilities of building the customized, all-fibre, broadband and bright light sources.

The silica nonlinear microstructured fibres, as presented in this paper, become compatible with standard fibre components and technologies (e.g. splicing, connectorization etc).

Supercontinuum generated in a small-core MSF is a very interesting nonlinear phenomenon from application-oriented point of view. A development of tailored dispersion of highly non linear silica MSF offers us the possibility of constructing a customized broadband light source.

Therefore, in the paper we present a theoretical and experimental investigation of dispersion characteristics of several different MSFs. Our studies are leading to the development of adapted dispersion properties, allowing construction of customized supercontinuum sources. All fibre, white light interferometry set-up, resulting in extremely high precision measurement of chromatic dispersion, is demonstrated, together with fully computer controlled fringe pattern analysis. Constructed set-up permitted comparison of chromatic dispersion measurements of microstructured fibres with modified fibre cross-section dimensions during the production process. High correlation between modelling and measured data gives possibility to control dispersion level in manufacturing process. Additionally, precisely designed and measured chromatic dispersion, especially around the zero dispersion wavelength, enables superior estimation of MSF nonlinear effects.

8426-24, Session 5

Influence of high power 405-nm multi-mode and single-mode diode laser light on the long-term stability of fused silica fibers

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As the demand for high power fiber-coupled violet laser systems increases existing problems remain. The typical power of diode lasers around 400 nm is in the order of 100 to 300 mW, depending on the type of laser. But in combination with the small core of single-mode fibers reduced spot sizes are needed for good coupling efficiencies, leading to power densities in the MW/cm² range. We investigated the influence of 405 nm laser light irradiation on different fused silica fibers and differently treated end-faces. The effect of glued-and-polished, cleaved-and-clamped and of cleaved-and-fusion-arc-treated fiber end-faces on the damage rate and behavior are being presented. In addition, effects in the deep UV were determined spectrally using newest spectrometer technology, allowing the measurement of color centers around 200 nm in small core fibers. The used fiber types range from low-mode fibers with different experimental dopants to single-mode and polarization-maintaining fibers as well as photonic crystal fibers. For this investigation 405 nm diode lasers using single-mode or multi-mode operation with 150 mW or 300 mW, respectively, were employed.

8426-25, Session 5

Mechanical reliability of micro-structured optical fibers: a comparative study of tensile and bending strength

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Micro-structured optical fibers are increasingly used in supercontinuum sources, fiber lasers and fiber sensor applications. In these applications the fibers need to be bent or strained. Whereas the tensile and bending strength of conventional telecommunication grade optical fibers has been extensively studied in the last two decades, the mechanical reliability of micro-structured remains insufficiently assessed. Their particular micro-structure, made of air holes running along the fiber, may affect their mechanical strength when compared to conventional step-index fibers. It is well known that optical fibers typically fail at the external silica surface of the fiber cladding and therefore the extra silica-air interfaces in micro-structured fibers could act as additional potential crack sources. It is hence crucial to characterize the mechanical reliability of micro-structured fibers in order to assess the range of stress and strain that they can sustain without being damaged.

We therefore carried out a systematic study of the mechanical reliability of micro-structured fibers under tensile load and in bending. The experiments have been performed on five micro-structured fibers with increasing outer diameters (from 100 to 250 µm), drawn for the same silica preform. The mechanical strength of these micro-structured fibers was compared with two reference fibers: a standard commercially available telecommunication grade optical fiber and a uniform silica fiber. We analyzed the experimental data using a two-parameter Weibull distribution. This approach allows comparing the mechanical strength of the different fibers and provides an indication of the defect distribution along the fibers. A visual inspection of the fractured surface of both bent and tensile tested fibers has also been conducted using scanning electron microscopy to identify the failure mechanism and to compare this mechanism to that of conventional fibers. Although the mechanical strength of micro-structured optical fibers is lower than that of the reference fibers, the experiments have shown that their failure strain of 4.3%, compared to 6.7% for the reference fibers, is adequate for many applications.

8426-26, Session 6

An improved non-linear nearly-zero dispersion flattened photonic crystal fibers with threefold symmetry core

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An improved dispersion flattened photonic crystal fiber is presented. This fiber has a threefold symmetry core that consists of a silica core surrounded by three low-index regions and three air holes. The main reason of such refractive index distribution is in avoidance of a high-index doped core, which is primarily responsible for high confinement loss. Therefore, confinement loss can be negligible over the considered wavelength range. The sufficient number of air hole rings in the fibers cross-section contributes to low confinement loss. It is shown through numerical simulation based on the full-vectorial finite difference frequency domain method that nearly-zero ultra-flattened dispersion can be obtained in the wavelength range from 1250 to 1700 nm. Desirable dispersion characteristics have been obtained by accurate tuning in diameters of low-index regions and also in diameters of particular innermost rings. The fibers' parameters are sensitive to deviations of geometry. Therefore, high attention should be paid to the fabrication process. The chromatic dispersion property with fabrication tolerances of 1 % and 2 % has been numerically calculated. A change of about 1 % affects the final flattened dispersion characteristics. However, the variations of the low-index regions affect the slope of the final dispersion and the parametric dispersion curves are crossed at one point. This point is found at the wavelength of 1550 nm by the tuning of all fibers' parameters and this implies negligible changes in the dispersion curve. Furthermore, the variations of low-index region geometry should not exceed 2 %. Finally, a fiber with five different arrangements of hole-to-hole spacing (pitch) is proposed. Each of them exhibits remarkable chromatic dispersion properties, such as nearly-zero ultra-flattened dispersion over wide wavelength range or zero dispersion at the wavelength of 1550 nm. The designed photonic crystal fibers have potential either in the field of nonlinear optics or in dense wavelength division multiplex systems.

8426-27, Session 6

Characterization of the propagation in photonic crystal fibers with the scalar-finite element method

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We could demonstrate in this work the applicability of the scalar- Finite Element method (SC- FEM) on PCF fibers to deduct several parameters of propagation and the chromatic dispersion. The SC- FEM has several advantages over the fully Vectorial (V-FEM). The main ones are that the SC-FEM has no spurious problem and the matrixes in the eigenvalue equation are small and symmetrical what contribute to numerical efficiency. The SC-FEM used in this work, for solving the partial differential equation of propagation in PCF, is based on the weighted residual methods, especially the Galerkin method.

In a first time, we studied the confinement of the fundamental mode according to several optogeometric parameters of the studied fibers as the ray of the holes, number of layers, distance between the holes, the wavelength. Then one was interested to the chromatic dispersion, a very important transmission characteristic and difficult to annul in the standards fibers for wavelengths lower to 1275 nm. Although the guiding mechanism of the PCF fibers considered in our work is identical to the one of the conventional fibers, the degree of liberty that they offer in term of control of the dispersion is very attractive. Indeed, a modification of the size of the air-holes in the cladding, or a strategic positioning of these will succeed to a modification of the total dispersion curve. With SC-FEM, we were able to determine the variation of the chromatic dispersion according to the wavelength and to the parameters of the structure of the PCF where we got wavelengths of zero dispersion around of 1000 nm.

8426-28, Session 6

Design of a low-bending-loss large-mode-area photonic crystal fiber

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We present a design of a photonic crystal fiber for high power laser and amplifier applications. Our fiber comprises a core with a diameter larger than 60 µm and exhibits single mode operation when the fiber is bent around a 10 cm radius at a wavelength of 1064 nm. Single mode guidance is enforced by high loss of higher order modes which exceeds 20 dB/m whereas the loss of the fundamental mode (FM) is lower than 0.05 dB/m. The fiber can therefore be considered as an active medium for compact high power fiber lasers and amplifiers with nearly diffraction limited beam output.

In our paper we describe the principle of the fiber design and we investigate the influence of the bend radius and of the bend orientation on crucial fiber parameters such as bending loss and mode field area.

In addition we analyze our fiber in terms of manufacturing tolerances. To do so we rely on a statistical design methodology. This analysis reveals the crucial parameters of the fiber that have to be controlled precisely during the fabrication process in order to achieve the required fiber performance. We also report experimental results obtained with a fiber fabricated according to our design that confirm the expected fiber performance.

8426-29, Session 6

Approximation of the effective refractive index of surface plasmons propagating along micron-sized gold wires in photonic crystal fibers

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Since the first presentation of selectively metal filled photonic crystal fibers (PCFs) in 2008, a lot of work and effort has been put in the understanding of propagation characteristics of such fibers which can be utilized as filters or polarizers.

A semi-analytical model for the implicit description of the effective refractive index neff of surface plasmon polaritons propagating along the metal wires has been developed and coupling of fiber core modes to such surface modes has been confirmed experimentally.

However, although there was made a simple ray-optical approach which describes the real part of the effective modes indices quite well, especially for higher order surface modes, the model fails for predicting the imaginary part (losses).

In this work we will present a numerical study of the propagation constants of the surfaces plasmons along the gold wires in photonic crystal fibers and show an improved analytical model based on the dispersion of a planar dielectric-gold interface. It properly describes both, the real and imaginary part of the effective refractive indices. Since the coupling of the fiber core mode to surface plasmon modes occurs at wavelengths where the phase of both refractive indices match, it is possible to predict regions of high losses in the transmission spectrum of such fibers without the use of finite element methods.

8426-30, Session 6

A low loss ultra-narrowband negative-dispersion and large mode field area photonic crystal fiber for dispersion compensation

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A hexangular lattice dual-concentric-core photonic crystal fiber is proposed, which is composed of an inner core to be formed by missing a central air-hole, an outer ring core to be produced by reducing the size of the air-holes of the third ring and the double cladding circle air-holes along the direction of fiber length. Based on the full vector finite element method with anisotropic perfectly matched layers, its dispersion, leakage loss and mode field area are numerically investigated. Numerical results indicate that the proposed fiber shows large negative dispersion, strong confinement ability of guide mode, large effective mode area and low leakage loss and low sensitivity to the structure parameters. And the wavelength of high negative dispersion value can be adjusted by artificially choosing the parameters of the proposed PCF, such as Λ, d1 and f. The optimal design parameters with Λ=1.2µm, f=0.92, d1=0.52µm for proposed PCF are obtained to achieve ultra-narrowband negative dispersion value for dispersion compensation. For the optimal design, the dispersion value reaches as high as -3400 ps km-1 nm-1 and the dispersion slope value is between -1000~ -6000 ps km-1 nm-2 over C band (1.53-1.565µm). At wavelength of 1.55µm, the leakage loss is closed to 10-2 dB m-1 and the corresponding area of effective mode is 36µm2.

8426-34, Poster Session

Polarization and dispersion properties of hybrid square-lattice photonic crystal fiber

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High level of birefringence in fiber optics is required to maintain the linear polarization state by reducing polarization coupling. Recently, due to the large index contrast of photonic crystal fibers (PCFs) compared to the conventional fiber, several highly birefringent (HB) PCFs have been reported by breaking the circular symmetry implementing asymmetric defect structures such as dissimilar air hole diameters along the two orthogonal axes, asymmetric core design and designing an air hole lattice or a microstructure lattice with inherent anisotropic properties such as the elliptical-hole PCF and squeezed hexagonal-lattice PCFs. Modal birefringence in these HB PCFs has been predicted to have values an order magnitude of 0.001 or 0.01 higher than that of the conventional HB fibers.

In fiber optic communication system, control of chromatic dispersion is no less important than control of polarization. Recently, the guiding and dispersion properties of square-lattice PCF have been reported by Bouk et al, for the first time. In the study, it has been demonstrated that the square-lattice PCF with the smallest pitch, that is 1 m, has negative dispersion in the wavelength 1.55 m without other artificial design in the cladding and core.

In this paper, we analyze the polarization and dispersion properties a hybrid square-lattice PCF by changing the hole-to-hole spacing and the air hole diameters. The proposed fiber exhibits high birefringence and negative dispersion with negative slope in the C band simultaneously. Modal birefringence and chromatic dispersion have been numerically analyzed by plane wave expansion method.

8426-46, Poster Session

Tellurite composite microstructured optical fibers with ultra-flattened zero dispersion

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Highly nonlinear microstructured optical fibers (MOFs) made of non-silica glasses have attracted much attention for their potential applications in wavelength conversion, parametric amplification and supercontinuum generation [1,2]. Tellurite MOFs are favorable media for nonlinear applications due to the high nonlinearity, wide transmission window, and good feasibility in fiber drawing process. Furthermore, the near zero and flattened dispersion is favorable for the design of highly nonlinear fibers exploiting effects such as four-wave mixing, self-phase modulation and Raman soliton [3,4]. However it is difficult to realize flat near-zero dispersion in highly nonlinear MOFs due to the large material dispersion and the low softening point of non-silica glasses. Despite this issue, we have reported fabrication of the first tellurite composite microstructured optical fiber (CMOF) with flattened dispersion profile [5]. Comparing with traditional MOFs the CMOF use different glasses in core and cladding region. This combination of step-index and air hole cladding provides an index profile as multi-ring holey design which is well-established in silica flattened dispersion MOFs. However the control of glass cladding is much easier than that of air hole cladding. Additionally, employing more rings of air hole, i.e. more layers of cladding will enhanced the properties of fiber such as propagation loss and flatness of dispersion. In this work we report an advanced tellurite CMOF that possesses two glass claddings and one ring of air hole cladding. TeO2-Li2O-WO3-MoO3-Nb2O5 glass with high refractive index at 1.55 µm n1550 of 2.082, TeO2-ZnO-Na2O-La2O3 glass with n1550 of 1.963 and TeO2-ZnO-Li2O-Na2O-P2O5 glass with low refractive index n1550 of 1.75 are used as the core, the first cladding and the second cladding, respectively. Six small air holes are located between the core and the first glass cladding. Such kind of fiber with ~1.6 µm core and ~0.7 µm air holes are fabricated by rod-in-tube method. Base on the SEM image chromatic dispersion is calculated by the fully victoria finite difference method (FV-FDM) and shows flattened chromatic dispersion (±3 ps/nm/Km) in the wide range from 1.55 µm to 1.72 µm. The nonlinear coefficient of present fiber is about 3.47 m-1W-1 which is much higher than that of silica MOFs. The confinement loss of this fiber is calculated to be less than 0.01 dB/m in the range of 1400 nm to 1800 nm, which is about 100 times lower than that of previou tellurite CMOF we publicated. Furthermore, broad and flattened supercontinuum generation is demonstrated in 30-cm-long fiber with femtosecond laser pumping at 1557 nm. This kind of fiber exhibits promising potential in nonlinear applications owing to the high nonlinearity and flattened dispersion profile.

[1] V. Kumar, A. George, J. Knight, and P. Russell, Opt. Express, 11(20), 2641-2645 (2003).

[2] J. Y. Y. Leong, P. Petropoulos, and J. H. V. Price et al., J. Lightwave Tech., 24, 183-190 (2006).

[3] K. Saitoh, M. Koshiba, T. Hasegawa, E. Sasaoka, Opt. Express 11(8), 843-852(2003).

[4] K. Hansen, Opt. Express 11(13), 1503-1509(2003).

[5] Z. Duan, M. Liao, X. Yan, C. Kito, T. Suzuki and Y. Ohishi, Appl. Phys. Express 4, 072502-072504(2011).

8426-47, Poster Session

All-fiber micro-machined Fabry-Perot strain sensor

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We present the design, fabrication process and experimental evaluation of a high-sensitivity, all-silica, all-fiber, micro machined Fabry-Perot strain sensor fabricated by two symmetrical micro-machined fiber sections. The sensor has short Fabry-Perot cavity and thus allows application of various signal integration systems such as low resolution spectral interrogation systems or white light systems. The fabrication process includes design and production of specially designed sensor forming optical fiber. This fiber includes central titanium doped region, phosphorus doped ring that surrounds titanium doped region and pure silica cladding. To produce a proposed sensor, two sections of sensor forming fiber are cleaved and etched in HF/IPA solution. Phosphorus doped region etches at considerable higher rate than other fiber sections and thus creates deep gutter at cleaved fiber surfaces. Titanium-doped region etches at the rate that is to some extent higher than etching rate of pure silica and thus creates slightly retracted surface relative to the pure silica fiber cladding. Etched fibers or optical elements are then re-spliced to create all-silica strain sensor. The sensor has thus long active length, while the length of the Fabry-Perot cavity can be adjusted by titanium doping level. Central titanium doped region also creates a waveguide structure that is used to deliver light to the cavity through one of the lead-in fibers. The sensor can be made compatible with single or multimode fibers. The proposed fabrication process is cost effective and suitable for high volume production. The presented design allows for efficient separation of sensor active length and sensor cavity length. We experimentally demonstrate 50 times longer active length than sensor's cavity length, which results in about 50 times more strain sensitive sensor when compared to sensors with simple cavity. The experimentally produced sensor forming fiber and sensors were designed to be compatible with standard telecom 50 µm multimode fibers. Strain tests were made with experimentally produced sensors, which were bonded onto the steel tests bars. The achieved strain resolution better than 0.8 µε, was demonstrated by the application of a commercial white-light multimode fiber-based signal processor. Combination of all silica design and short air cavity results in sensor's low intrinsic temperature sensitivity. The intrinsic sensor temperature sensitivity was tested by placing a non-mounted sensor into the temperature controlled oven. The sensor was exposed to temperatures exceeding 650 °C, without observable damage. The intrinsic temperature sensitivity proved to be below 0.12µε/°C.

8426-48, Poster Session

Narrow band amplification and tunability in a two-turn erbium-doped microfiber coil resonator

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In this paper, we present a new structure for rare-earth doped fiber amplifiers which is composed of microfiber coil resonator (MCR). Based on the steady state approach of the light propagation in microfiber coil, we numerically analyze the modified coupled mode equations of optical amplifier for signal and pump simultaneously, considering the effect of rare earth element doped in fiber. It is shown that by using microfiber, we can obtain a large gain with a very short length of several millimeters, as compared with conventional erbium doped fiber amplifiers (EDFA). Optical gain characteristics of this system, which depend on device parameters such as amplifier length, microfiber radii and pitch between adjacent turns, are investigated. Also, variations of optical gain versus the nonstructural variables, such as signal and pump wavelengths, and intensity of signal and pump light are shown.

This MCR structure, amplifies only the wavelengths that lies in resonance conditions. It can be seen that bandwidth of this device is very narrow, in the order of several picometres. However by changing some parameters such as pitch and microfiber radii, amplifier bandwidth will be increased. On the other hand, with these changes, resonance condition varies and amplification occurs in another wavelengths. Thus, this amplifier acts as a tunable device. In this case, optical gain will be decreased, but with optimizing pump and signal intensities, this issue will be resolved to some extent.

Chalcogenide and bismuth silicate microfibers demonstrate very large nonlinearity compared with a telecom single mode fiber, which can be incorporated in ultra-fast photonic devices and pulse shaping applications. Using the characteristics of these materials in our model, we compare variations of signal gain in terms of input signal and pump intensities, in two cases: linear and nonlinear Kerr effect.

8426-49, Poster Session

A thermally scanned all-fiber interferometer based on vanadium-doped fiber

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This paper presents an all-optically controlled all-fiber optical path length modulator. The presented system takes advantage of a heating effect induced in vanadium-doped single-mode fiber through laser excitation. The vanadium doped fiber was produced by MCVD using flash vaporization doping process. The presented system can be applied in various applications, for example in white-light interferometry.

The system consists of Michelson interferometer with vanadium-doped fiber in one arm, 980 nm excitation high-power laser diode capable of generate up to 750 mW of optical power and 1310/1550 nm signal sources or channels. Due to spectral absorption properties of vanadium ions in silica, the absorbed optical power emitted by 980 nm source is mostly converted via non-radiative relaxation process into heat in the vanadium-dope fiber, while the absorption at 1310/1550 nm remains low. The rise of fiber core temperature causes the change of fiber core refractive index and consequently the change of optical path difference in one of the interferometer arms. For continuous scanning of the optical path length the extinction laser diode operates in pulse mode. The vanadium-doped fiber is therefore periodically heated and cooled. The optical path length difference of scanning interferometer is simultaneously measured with high-coherence source which provides the required reference trace. By signal processing of the interference pattern obtained at 1550 nm using high-coherence source, the optical path length difference of the scanning interferometer can be reconstructed at any time. In addition the white-light source was also applied to perform white-light interferometry at 1310 nm.

The achieved modulated optical path length was over 150 µm when using 20 cm long vanadium doped fiber and 750 mW 980 nm pump laser in one arm of Michelson interferometer. The time constant of the system proved to be below 1 s. The all-optical configuration of the scanning interferometer allows for remote and electric components free control of the optical path length difference in various fiber optic systems. In particular the proposed design is suitable as an interrogation system for various sensors, where the absolute optical path length variation/ measurement is required.

8426-50, Poster Session

Design and experimental evaluation of a multi-core fibre with low macrobending-induced crosstalk and optimized fan-out/fan-in solution for application in telecommunications

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Multi-core fibres (MCFs) have recently gained much attention as a promising candidate for the next generation long-haul transmission links. The intense and extensive research effort made in this field is constantly motivated by the necessity of finding a solution to anticipated capacity crunch as a result of the capacity limits of currently used optical links. MCFs will potentially allow to introduce a large scale-up per fibre capacity, especially while combining with others multiplexing techniques along with significant cost reduction comparing to standard, single core fibres. However, to become a real, commercial alternative, this technology has to overcome set of technological problems and challenges as well as offer comparable performance in terms of loss, chromatic dispersion, polarization mode dispersion, etc. Among others, two aspects can be crucial to address, namely the crosstalk and compatibility with existing systems.

In this paper we present results of numerical investigation, fabrication and experimental evaluation of a nineteen cores MCF. At this phase fibre design was focused on minimising the crosstalk between cores and core numbers scalability, as these properties seems to be fundamental for successful application for MCFs as a long-haul transmission links. Further, we also demonstrate a novel solution for all-fibre fan-out/fan-in device optimised for providing flexibility and compatibility with wide range of standard components used in telecommunications systems as well as standard telecommunications fibres.

8426-51, Poster Session

Large core microstructured fibers with asymmetric cladding design for practical single-mode operation

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We have successfully designed and implemented a few series of silica-based microstructured optical fibers (MOFs) with the asymmetry

intentionally introduced into the typical triangular cladding configuration. The adaptations included MOF with the core shifted for the pitch value from its usual location in the center of the lattice and MOF with the reduced number of air holes giving in the end so called 'incomplete cladding' structure. All fibers were made by a conventional stack-and-draw method and the air content in each series was regulated by varying two essential technological processes - capillary pressure and drawing temperature. Initially, presented structures were supposed to satisfy a set of special requirements: large core dimensions (up to 40 μm), significant difference in optical losses of the first two modes (LP01 and LP11), practical fundamental mode operation with the beam quality M2 = 1.0, high bending resistance properties resulting in the expanded spectral operating region as compared to traditional MOFs, fiber placement on a standard transport spool of 16 cm in diameter. The accurate control over the impurity of the higher order mode in the output pattern was provided by means of diverse techniques: registration of the near- or far-field distribution on a CCD-camera screen and modal beats analysis. Taking into account abovementioned circumstances, we could guarantee favourable conditions for the enhancement of the higher order mode attenuation by reason of increased leakage of the mode optical power through the silica spaces between the air holes into the outer fiber cladding. So the attenuation coefficient of the higher order mode was estimated to be in the vicinity of 2-10 dB/m, large enough to ensure single-mode regime at a fiber length starting from 5 m. Ultimately, we have yielded impressive results: robust single-mode operation, improved bend performance (operability on a 16-cm-diameter spool), expanded range of working wavelengths (for 300 nm).

8426-52, Poster Session

Progress in the fabrication of rare earth doped aluminophosphosilicate optical fibers by the granulated silica method

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We present our progress in the production of Erbium (Er) or Ytterbium (Yb) doped active optical fibers fabricated by the granulated aluminophosphosilicate optical glass method. Fiber fabrication from granulated oxides allows manifold designs of fiber microstructures but has the drawback of scattering losses, that originate from glass inhomogeneities and micro bubbles. With this work we aimed at minimizing these losses.

We present advantages and disadvantages of mixing the oxides directly or by using the Sol-Gel method. For both methods we studied the effects of varying the dopant concentrations and of introducing iterative melting and milling procedures. In particular, the Sol-Gel method allows the easy inclusion of P2O5 and thus, in combination with Al2O3, higher dopant concentration of Yb and Er are possible. Furthermore, photodarkening is reduced.

For our comparative study we determined volume percentage and distribution of chemical elements in the fabricated fiber glasses by the analytical technique of Energy-dispersive X-ray and the amount of crystallization by X-ray diffraction analysis. Furthermore we measured fluctuations of the refractive index profile and scattering losses of the fiber core

8426-53, Poster Session

Dispersion properties of all-solid photonic crystal fibers with nanostructured core

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The development of all-solid photonic crystal fibers for nonlinear optics is an alternative approach to the air-glass solid core photonic crystal fibers. The use of soft glasses ensures a high refractive index contrast (> 0.1) and a high nonlinear coefficient of the fibers. In addition, the manipulation of the subwavelength structure of the core of a photonic crystal fiber allows significant modification of it's dispersion characteristics and the efficient generation of a supercontinuum with various femetosecond and nanosecond sources. The development of all-solid photonic crystal fiber allows very accurate control of all the parameters of the developed fiber in very good agreement with the design criteria.

In this paper we report on the dispersion management capabilities in all-solid photonic crystal fibers with nanostructured core using thermally matched glasses, which can be jointly processed using the stack-and-draw fiber technique. We consider a photonic crystal fiber made of the high index lead-silicate glass SF6 and the in-house synthesized low index silicate glass NC21. The NC21 glass plays the role of low index inclusions in the photonic cladding and nano-inclusions in the core of the fiber. For modeling purposes, we assume various lattice constants in the range of 1.2-2μm and a complex photonic cladding. The first ring is responsible for the general dispersion properties of the photonic crystal fiber. We assume a cladding filling factor of over 0.9 in this ring. The remaining 6 rings are responsible for the single mode performance of the fiber. The filling factor within these rings is 0.4. The final dispersion characteristic of the photonic crystal fiber is determined by the low index nano-inclusions in the core with diameters in the range 100-500nm. As a result of this modeling effort, we have designed structures with an ultra-flat near-zero anomalous dispersion below 10ps/nm/km over 350nm dedicated to supercontinuum generation with 1550nm laser sources. Other structures with over 450nm broadband flat normal dispersion are also presented and discussed.

8426-54, Poster Session

Analysis of up-conversion pumping schemes in erbium doped tellurite fibers

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Increasing number of possible applications in industry, medicine, entertainment and others creates continuous demand for compact and efficient, coherent light sources operating in the visible part of spectrum. Fiber lasers, combining the advantages of high efficiency, compactness, relatively high power outputs and natural tendency to single spatial mode operation, are continuously considered as one of the most interesting and promising approaches. This applies specifically to blue-green and orange spectral range of operation, available to a limited extend to semiconductor lasers. It is well known that up-conversion lasing is supported only by limited number of low-phonon glassy hosts, like e.g. ZBLAN glass, doped with selected rare-earth ions, among which Er3+ seem to be the most promising in the context of green emission and lasing. Apart from green emission erbium ions offer also optical transitions in the violet and red spectral range, observable under up-converted excitation at several infra-red and red wavelengths.

This work is focused on analysis of multi-photon and multi-ion excitation mechanisms resulting in

IR-to-visible up-conversion in low-phonon tellurite glasses doped with erbium ions and discussed in the context of the efficiency of the individual pumping schemes and lasing properties of such system. Several samples of bulk tellurite glasses (with chemical composition 78TeO2-11ZnO-11Na2O, abbreviated TZN) and tellurite fibers, differing in activator's concentration were carefully examined by means of highly resolved laser spectroscopy with specific attention concentrated on possible up-conversion processes resulting in red, green and violet emission under infrared and red pumping by a commercially available semiconductor lasers diodes. The recorded absorption and emission spectra, fluorescence dynamics profiles and luminescence versus pumping power intensity dependencies allowed determination of fundamental spectroscopic parameters (like emission and absorption cross section and fluorescence lifetimes), which, in turn enabled rate-equation based modeling and analysis of up-conversion processes responsible for observed behavior. The modeling results have led to identification of the involved processes and finally allowed comparison of different pumping schemes with respect of their efficiencies, giving a good starting point for optimization and development of erbium doped up-conversion fiber laser based on tellurite glass.

8426-55, Poster Session

Mode conversion in hybrid optical fiber coupler

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Designing of all in-line fiber optic systems with a supercontinuum light source gives some issues. The use of a standard single mode fiber (SMF) as an input do not secure single mode transmission in full wavelength range. In the paper, the experimental results of the tested hybrid fiber optic coupler were presented. It was manufactured by fusing a standard single mode fiber (SMF28) and a photonic crystal fiber (PCF). The fabrication process is based on the standard fused biconical taper technique. Two types of large mode area fibers (LMA8 and LAM10 NKT Photonics) with different air holes arrangement were used as the photonic crystal fiber. Spectral characteristics within the range of 800 nm - 1700 nm were presented. All process was optimized to obtain a mode conversion between SMF and PCF and to reach a single mode transmission in the PCF output of the coupler.

8426-56, Poster Session

Chemical sensor of liquids based on suspended-core fiber

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A photonic crystal fibre is a special microstructure optical waveguide made by stacking capillaries and rods. Thanks to that microstructure, such fibres have unique optical properties which have various applications in atomic and molecular physics and quantum optics.

We describe our attempts at investigation of optical phenomena in microstructure optical fibres with suspended core. The small size of the core (about 1 micrometer) of those fibres gives rise to evanescent wave in the air channels. That light could allow coupling between light and atoms or molecules, which are introduced into the holes. We would like to use this coupling for analysis of medium inside the fibre. In the previous works, suspended core photonic crystal fibres filled with liquids or gases were used for measuring numerous physical quantities. Particularly, our group focused on examination of absorption spectra of a liquid-filled fibre.

Many experimental groups presented various ideas of filling the microstructured fibre. The easiest method is to dip a fibre tip in a medium and to use capillary forces or a diffusion effect.

In the presented work, aqueous solutions of the oxazine 725 perchlorate was used for filling the suspended core fibre by dipping method. The oxazine 725 perchlorate (3,7-bis(diethylamino)phenoxazin-5-ium perchlorate) is a cationic organic compound with an interesting electronic structure. It is used as an electron acceptor in different chemical and biochemical processes and also in dye lasers. In our study with suspended core fibres, we concentrated on applications of this research in the liquid sensing subject. Preliminary studies demonstrate an increased sensitivity of such sensors for absorption measurements relative to standard cuvettes.

8426-57, Poster Session

Designing a special-cut dual-core photonic crystal fiber for pressure sensing applications

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Photonic crystals are extensively used as 900 bent waveguides, filters, lasers, amplifiers, resonators and nonlinear devices. Their utilization as sensors is a new field of research that seems to be promising because they are compact, high sensitive, and even easy to fabricate. In this paper we present a novel design for sensing the mechanical force (pressure) based on the intensity variations of interference pattern of fundamental mode of a dual core photonic crystal fiber (PCF). When a dual core PCF is exposed to a radiation beam, the two cores acts as separated and independent sources of light and their interference patterns can be saved on a screen. Since single-mode propagation of PCFs is one of the outstanding properties that has made them attractive for beam propagation over a wide range of wavelengths, almost any wavelength can be used for this type of sensor. Now by exerting a mechanical force to the PCF, one can realize the change of the shape and intensity of interference patterns compared to pre-exerting case. These patterns alterations however, are apparently complicated and single mode fibers are then needed to avoid such complications. Moreover, the design should be in such a way that minima number of modes is allowed and guided in the cores with well defined polarization. One major feature of our design is a special cut of the fiber. If two parallel hypotenuses are cut from the top and down sides of a PCF, the mechanical force applied on fiber circumference and its induced stresses will then be most transferred into the central region of the fiber. This type of fiber cutting not only allows maximum conductance of pressure to central part of the fiber, but also provides more sensitive sensor as will be discussed later. Using the Franhoufer diffraction integral, the interference pattern formed on the screen can be modeled. The results show that the intensity reduction due to mechanical force is linear with the pressure up to about 10Mpa. A simple linear fit gives a slope of 0.024Wm-2/MPa that represents the sensitivity of the sensor.

8426-58, Poster Session

Femtosecond and UV inscribed grating characterization in photonic crystal fibers: optimization for sensing applications

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Photonic Crystal Fibers (PCF) remain an interesting and novel fibre type and when suitably designed can prove to be “ideal” for sensing applications, as the different geometrical arrangement of the air holes alters their optical waveguiding properties, whilst also providing tailored dispersion characteristics. As a result of the absence of rigid boundaries in core-cladding interface, light travels in the same material minimizing material dispersion effects, this plays a strong influence on the waveguidance of conventional optical fibres. This impacts the performance of grating structures, which offer wavelength encoded sensing information. It is widely recognized that the inscription and characterization of UV and femtosecond fibre Bragg gratings (FBG) and long period gratings (LPG) in such fibres is of great importance. In this paper we undertake a study of the role of fibre grating structures in photonic crystal fibres. Our work is divided to two steps. Initially, a modal analysis is presented in order to evalulate bound modes for a number of fibre structures that are deamed suitable for grating inscription, using either UV or femtosecond lasers. Here we will utilise the full vectorial finite element method (FEM), which is applied in order to ascertain the effective refractive indices. In a second step we proceed with characterization of the FBG and LPG that have been inscribed within the PCF. For that

purpose we implement the bi-directional beam propagation method (BiBPM). Furthermore, we analyse the phase matching condition for LPG in PCF, where we systematically investigate the dispersion curves, thereby revealing how the grating period is modified in proportion to the resonant wavelength in order to optimise the grating dispersion curve for turning point determination, thereby increasing sensor sensitivity.

8426-59, Poster Session

Modeling microfluidic flow and heat transfer in circular and elliptical channels in microstructure fibres

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Micro-fluidics have been considered as important micro-scale devices that can be used to manipulate very small volumes of fluids on the order of nano- to femto-litres. The control and sorting of nano-particles is a primary goal using this technology. Moreover, the analysis of DNA in the fluid streams has proven of great interest for the high throughput of chemical and biological analysis. There is particular interest in the use of microstructure optical fibres for the transfer of fluids, whereby the guided light interacts with a fluid in the region of the air-hole structure. Indeed microstructure fibres are considered as strong candidates for their use as micro-fluidic devices, given the minute sample volumes that are required, and as optical fibre sensors with applications in chemical and biological sensing. Given the development of new types of microstructure fibres with cross sections containing circular or elliptical holes, or more complex cross sectional geometries, it is important to be able to model the fluid transport capabilities of these fibre types. Furthermore, complex cross sectional geometries can affect the transfer of heat into the fibre, creating local changes in the behaviour of the fluid system. In this paper these aforementioned effects are studied using a numerical application of a system of partial differential equations consisting of the time-dependent Navier-Stokes equations and the convection-diffusion equation. We examine the effects of flow rates, fluid viscosity, compressibility and the channel diameter. The role of heat flux is considered in relation to the fluid characteristics, but also with regard to the material properties of the microstructure fibre.

8426-60, Poster Session

Spatial optical filter using hollow core silica tube for sensing applications

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In this work, a spatial optical filter based on a hollow core silica tube is presented. Due to the core dimensions, it is possible to obtain a periodical spatial filter ranging from 1200 to 1700 nm with a wavelength peaks separation of 13 nm. The bandwidth is approximately 5 nm, and the isolation loss of 30 dB. The optical losses are of approximately 4.5 dB/cm. Different spatial optical filters were made, by using different lengths and all the spectra obtained were identical. Therefore, the behavior of the spatial optical filter is independent of the length. The 40 mm long spatial optical filter was tested as a sensing element, and subjected to different physical parameters. When the longitudinal strain and temperature are applied, the spatial filter is wavelength sensitive. However, when the sensing head is immersed in different refractive index liquids the optical power decreases. The sensing head is also characterized in axial strain, evidencing insensitivity to this parameter. This sensing head can be used for extreme conditions, as high temperatures, where it presents a sensitivity of 0.02 pm/°C.

8426-31, Session 7

On the influence of hexagonal lattice photonic crystal fiber parameters on femtosecond grating inscription

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Photonic crystal fibers (PCFs) have been extensively studied mainly owing to their design flexibility. Their internal microstructure can be tailored to achieve a wide range of optical guiding properties, suitable for many different applications. Fiber Bragg grating fabrication in such fibers is now being investigated and developed to enable new fiber sensor and all-fiber laser applications. Grating writing in PCF is not necessarily straightforward. This is due to a large extent to the air hole microstructure in the fiber cladding which impedes the inscribing beam to reach the fiber core in sufficient amounts. This issue is more pronounced for multi-photon grating inscription techniques, for which the intensity of the light reaching the core is crucial to induce the desired refractive index change.

We performed a numerical study of transverse light propagation through the cladding into the core for various hexagonal lattice PCFs. A numerical tool based on commercial FDTD software was developed for that purpose. To assess the influence of the PCF microstructured cladding, we defined a figure of merit to quantify the amount of laser light reaching the core: the “transverse coupling efficiency” (TCE). We studied the influence of the hexagonal lattice parameters, in particular the air hole radius and pitch, on the energy reaching the core for various angular fiber orientations. Our study of the TCE dependence was performed for ultraviolet and infrared femtosecond laser sources. As a result we have identified favorable PCF lattice parameters and a fiber orientation that would allow efficient femtosecond grating inscription. For the first time we show that the microstructure of a PCF can not only have a limiting, but also a constructive influence on the laser energy reaching the core of the fiber and thus on the efficiency with which gratings can be inscribed.

8426-32, Session 7

Low-loss multimode interference couplers for terahertz waves

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The terahertz (THz) frequency region of the electromagnetic spectrum is located between the traditional microwave spectrum and the optical frequencies, and offers a significant scientific and technological potential in many fields, such as in sensing, in imaging and in spectroscopy. In the recent years, the rapid development in sources, receivers and detectors of THz waves has led to the emergence of great research activity in the waveguiding properties of these waves, both as a part of active and passive components, such as lasers, detectors, or filters, and also the basic building blocks required to connect various components in a system. However, waveguiding in this intermediate spectral region is a major challenge. Amongst the various THz waveguides suggested, the metal-clad waveguides supporting surface plasmon modes waves and more particularly hollow core structures, coated with insulating material are showing the greatest promise as low-loss waveguides for their use in the active components and as well as passive waveguides. Optical power splitters are important components in the design of optoelectronic systems and optical communication networks such as Mach-Zehnder Interferometric switches, Sagnac interferometers, polarization splitter and polarization scramblers. Several designs for the implementation of the 3dB power splitters have been proposed in the past, such as the directional coupler-based approach, the Y-junction-based devices and the MMI-based approach. The ease of fabrication, compactness, low-loss, wide bandwidth, excellent splitting ratio and low polarization

dependence of the Multimode Interference (MMI)-based devices are features which have attracted more and more attention for use as building blocks in several photonic integrated circuits and wavelength-division multiplexing (WDM) networks. In the present paper a novel MMI-based 3dB THz wave splitter is implemented using Gold/polystyrene (PS) coated hollow glass rectangular waveguides. The H-field FEM based full-vector formulation is used to calculate the complex propagation characteristics of the waveguide structure and the finite difference time domain (FDTD) approach to estimate the performance of these power splitters.

8426-33, Session 7

Modeling of photonic crystal fiber with polymer inclusions

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Photonic crystal fiber (PCF) enables the infiltration of advanced materials and liquids such as liquid crystals, high index liquids, biolayers, ferrofluids, metals as well as polymers into the air-holes of the PCF. Infiltration of the air-holes provide this way the ability to modify the guiding properties and behaviour of the fibers in order to act as tunable devices, filters, attenuators, sensors etc. A comprehensive numerical study of guiding and thermal properties in a hybrid photonic crystal fiber infiltrated with polymer is presented. In our calculations, we consider poly-dimethylsiloxane (PDMS) as the active polymer into the air-holes of the PCF and we investigate the guiding properties of the hybrid structure for different relative hole sizes (d/Λ= 0.35, 0.45, 0.55, 0.65, 0.75) at different wavelengths. The presented results were compared in parallel with a conventional air-filled PCF and we show how the polymer material affects the guiding mechanism of the fiber in terms of the effective index of the fundamental guiding mode (neff), effective modal area (EMA), confinement and total loss of the fiber, numerical aperture (NA), cut-off wavelength (V-parameter), and the fraction of evanescent field of the guiding mode inside the infused material for wavelengths ranging from 500 nm to 1700 nm. Furthermore, we show how the aforementioned parameters can be thermally tuned for temperatures between 0°C and 100°C at two different operating wavelengths (633 and 1550nm). The main advantages of such hybrid structures can directly offer a number of advantages such as conversion of a multimode PCF to endlessly single mode, tunability of EMA and NA, increase of the evanescent field overlap of the guiding mode with up to 16% of the power being in the cladding, etc.

8426-35, Session 7

Beam quality alterations due to heat generation in photonic crystal fiber lasers

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Photonic crystal fiber lasers (PCFLs) have gained much interest due to their ability to deliver high power with considerable stability, excellent beam quality, compactness and maintenance ease. For large-mode-area fiber lasers (LMAFLs), delivered and out put powers up to 360W and 260W respectively has been reported for a 4m long fiber, for instance. Respecting to these high delivered powers, one should be worried about the heat problems in the fiber body. Although the large surface to volume ratio can remove the heat much more efficient than solid-state counterparts, however in high power regimes the heat transfer mechanisms, namely convection and radiation, can not be such effective. More ever in holey fibers, we encounter with a thermal insulator layer made by air holes that reduces the heat transportation from the inside to the outer surfaces of the fiber. The temperature gradient produced across the fiber cross section can alter the refractive index via thermal dispersion or dn/dT effect. This effect leads to modifications in transverse profiles of mode propagating along the fiber, so the beam quality or M2 factor can be affected. This work investigated the heat effects on the beam quality of propagation modes in a PCFL. For this, we considered an air-clad ytterbium-doped LMAFL in which the core has been established with ignoring three holes in a triangle lattice. We first calculated the temperature distribution across the fiber cross section. Then, the electric fields were simulated under thermally-induced refractive index changes. Finally, the M2 factor has been calculated by multiplication of beam profile widths in r and k-space in together. The results showed moderate changes for fundamental mode of HE11 whose polarization is linear while for TE, TM and EH modes, the variations in M2 factor were pronounced. The details of results will be come in full paper.

8426-36, Session 8

Brillouin fiber laser using AsSe suspended-core chalcogenide fiber

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Brillouin fiber lasers (BFLs) have recently attracted much attention for many applications due to their extremely narrow linewidth [1]. Chalcogenide microstructured optical fibers (MOFs) are an attractive option to make BFLs because of the high Brillouin gain coefficient in chalcogenide fibers, which is about 140 times greater than in standard silica fibers [2, 3]. Furthermore, the use of MOFs enhances the nonlinearity in the chalcogenide fiber [4] and allows for a small effective area structure, which can lower the laser threshold as well as the laser cavity length.

In this paper, an all-fiber Brillouin laser ring cavity using a 3-m-long suspended-core chalcogenide AsSe fiber is reported for the first time to our knowledge. The Brillouin gain coefficient in the fiber was experimentally measured to be 6.10–9 m/W. For a non-resonant ring cavity with no servo-locking, a laser threshold power of 37 mW and an efficiency of 30% were obtained. The linewidth of the BFL and the pump laser were respectively measured to be below 4 kHz, the resolution of our autocorrelator, and 250 kHz, thus showing the linewidth-narrowing nature of the BFL. This result paves the way to compact Brillouin lasers with low threshold power and good spectral purity.

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[1] S. Smith et al, Optics letters 16(6), pp. 393-395, 1991.

[2] K. Abedin, Optics Express 13(25), pp. 10266-10271, 2005.

[3] C. Florea et al, Optics Express 14(25), pp. 12063-12070, 2006

[4] D. Nguyen et al, IEEE Photonics Technology Letters 22(24), pp. 1844-1846, 2010.

8426-37, Session 8

Enhanced stimulated Brillouin scattering in tellurite microstructured fibers

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The recent development of highly nonlinear microstructured fibers has opened new horizons to compact nonlinear devices for applications such as fiber lasers, distributed fiber sensors, and Brillouin amplifiers. In such applications, the stimulated Brillouin scattering (SBS) effect, which

can be enhanced in a highly nonlinear structures such as the emerging tellurite fibers, is useful to amplify a narrow band optical signal by propagating in a direction opposite to the pump. In our contribution, we report on full modal analysis and comparison with experimental results of the SBS in small core microstructured tellurite fibers. To the best of our knowledge this is the first report of SBS in microstructured fibers made by tellurite glass.

Our analysis is firstly made in four air-holes different tellurite microstructured fibers and compared to silica and chalcogenide fibers. Such fibers have drawn much interest because of their capacity of increasing the SBS gain. An enhanced Brillouin gain coefficient, gB, of 1 10-10 m/W is found around the acoustic frequency of 8 GHz. Therefore, very low Brillouin threshold powers were found to be sufficient to generate backscattered Brillouin-Stokes component for short lengths of the tellurite microstructured fibers. Then, we used real scanning electron microscope images of small core highly nonlinear tellurtie fibers and compared the SBS parameters to numerical predicted results. Good agreement is found between the SBS gain coefficients and the frequency shifts.

8426-38, Session 8

CW parametric generation in polarization maintaining PCF pumped by Yb-doped laser

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Phase matching curves for several types of parametric processes are studied in a polarization maintaining photonic crystal fiber (PCF) LMA5-PM. The recent progress in Yb-doped fiber lasers operating in the spectral range of 1.02 - 1.1 μm stimulate us to extend that range due to parametric process. The dispersion characteristics of the PCF LMA5-PM make it suitable both for up and down conversion when pumped by an Yb-doped fiber laser source. This work presents experimentally and numerically obtained possible phase-matching curves for scalar and pump-divided vector four wave mixing (FWM) parametric processes, when pump is propagating at the both fiber's birefringent axes. We used pump wavelengths on both sides of the fiber's zero dispersion wavelength being of about 1053 nm. We observed two branches for scalar FWM corresponding to low and fast group-index modes shifted by 1.5 nm from each other. Moreover due to birefringence matching of two so called negative and positive branches for vector FWM process were also obtained similar to those obtained for PCF with 674 nm zero dispersion wavelength, see [J.S.Y. Chen et al, Optics Letters, 31, 873 (2006)]. To observe a CW FWM a signal CW seed was used. Experimentally, we have demonstrated a parametric conversion with the largest frequency shift of 100 THz from the pump laser operating at 1016 nm, thus generating the anti-Stokes wave at 758 nm. Good agreement has been observed between the measured wavelength shifts and those obtained by numerical simulation. The analytical solution has been deduced both for the scalar and for the vector pump-divided FWM. A good agreement between the analytical solution and the experimental data for parametric shifts up to 60 THz makes it possible to estimate fiber dispersion and birefringence parameters from experimental parametric shifts.

8426-39, Session 8

Development of large-core photonic crystal fiber for hyperspectral transmission

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There is increasing demand for mid infra-red optics in the spectroscopic and optical sensor application areas. The practical use of such systems for mid IR sensing requires the development of novel optical passive components that can be easily integrated with a wide range of sources and detectors.

In this paper we present the development of a large core multimode photonic crystal fibre with hyperspectral transmission that covers the visible, near and (in part) mid infra-red wavelength ranges (400-6500 nm). We have optimised the composition of a heavy metal-oxide glass based on the PbO-Bi2O3-Ga2O3 system modified with Nb2O5, Ta2O5, SiO2, GeO2, BaO, CdO, Na2O and K2O. The optimised glass shows good transmission up to 6 μm as well as good rheological properties that permits multiple thermal processing steps in an optical drawing tower without crystallisation. The selected glass is synthesized in-house and has been used for fibre development. We have fabricated a multi-mode photonic crystal fibre with an effective mode area of 120 μm2. The photonic cladding is composed of 5 rings of air holes with a fill factor of 0.6. The transmission of a hyperspectral spectrum is experimentally verified using a supercontinuum source. The attenuation of the fibre and its sensitivity to bending losses is presented. In addition, a demonstration of the use of the photonic crystal fibre for mid IR transmission with LED sources is presented and discussed.

8426-40, Session 9

Novel block copolymers for multiagent detection using polymer optical fibers

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Photonic sensors based on platforms of low cost and complexity like Plastic Optical Fibers-POF exhibit favorable characteristics suitable for real exploitation in emerging applications requiring even wireless sensing networking. Further to the exhaustive exploitation of photonics platforms and designs such as in PCFs, BGs etc it has been recognized that specially designed optical materials could greatly enhance the functionality of certain sensing devices.

We propose here for the first time the use of a new class of specially engineered polymers, namely the block co-polymers BCP [1] offering a high degree of customization, applied successfully to a low cost POF platform [2]. As a special case we demonstrate the use of a BCP consisting of two blocks, one hydrophilic and sensitive to polar substances and the other hydrophobic and sensitive to hydrocarbons. Theoretical prediction of polymer's behavior in measurands' presence has been successfully confirmed experimentally. The existence of two different blocks allows for the detection of a wide variety of agents and this response could be further enhanced or differentially modified by suitable adjusting the ratio of the two co-polymers.

Using methanol as polymer's solvent we successfully coated PMMA POF without deteriorating its properties. Functionalized sensitive U-bent POFs were employed as sensing tips overcladded with BCP using a simple dip coating technique. Due to BCP's high transition temperature Tg (well above 120oC) the overlayers were very stable and environmentally robust. The developed sensors' exhibited very fast response (few seconds) in ammonia, humidity, benzene and in specific proteins like lysozyme, at detection limits lower to 1%w concentration. The sensors did not exhibit any degradation after continuous measurements cycles even when subjected to different measurands' sequentially, but instead they were fully reversible in contrast to other optical sensors based on polyaniline or metal-oxides that usually suffer from a fast performance's deterioration.

[1] S. Pispas et al. "Development and optical properties of cadmium sulfide and cadmium selenide nanoparticles in amphiphilic block copolymer micellar-like aggregates", J. Phys. Chem. C 2007, 111, 15201.

[2] L. Athanasekos, et.al, "Laser microstructuring of polymer optical fibres for enhanced and autonomous sensor architectures", Proc. Eurosensors XXV, September 4-7, 2011, Athens, in Procedia Engineering Elsevier

8426-41, Session 9

Development of large core microstructured polymer optical fiber

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In this paper we report the development of a large core micro-structured polymer optical fibre (mPOF) based on in-house synthesized optical grade PMMA. In order to insure that the polymer is amorphous and atactic, free radical polymerisation is used. Initial fabrication runs resulted in samples with transmissions (through 5mm samples) of above 85% for a wavelength of 1550 nm and above 90% for 850 nm and 1300 nm. For the fabrication of the initial polymer based large core photonic fibre, the stack and draw method is used. This method is used as it allows the fabrication of longer preforms than by drilling polymer and, furthermore, it will simplify the fabrication of two (or more) polymer structures in the future. The drawing process for the chosen polymers is a low temperature process conducted at temperatures not exceeding 200oC. This relatively low temperature regime is chosen as most notable problems encountered during this stage are the heat degradation of the polymer and the elongation of the polymer chains under applied pressure. Due to the thermoplastic properties of PMMA, multiple drawings are possible.

We have designed an mPOF with a core area of 50 µm2 and single mode performance at a wavelength of 650 nm. The photonic cladding is composed of 4 rings of air holes with a filling factor of 0.4 ensuring single mode performance at the design wavelength. The mPOF fibre design was fabricated using the stack and draw technique and some deformation of the structure of the photonic cladding has been observed during final stage of fibre drawing. The influence of this development imperfection on the overall fibre performance has been modelled. Finally the optical properties of the fabricated fibre were measured and a comparison between these and the modelled properties was made.

8426-42, Session 9

Fiber design and realization of point-by-point written fiber Bragg gratings in polymer optical fibers

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An increasing interest in making sensors based on fiber Bragg gratings (FBGs) written in polymer optical fibers (POFs) has been seen recently. Mostly microstructured POFs (mPOFs) have been chosen for this purpose because they are easier to fabricate compared, for example, to step index fibers and because they allow to tune the guiding parameters by modifying the microstructure.

Now a days the only technique used to write gratings in such fibers is the phase mask technique with UV light illumination. Despite the good results that have been obtained, a limited flexibility on the grating design and the very long times required for the writing of FBGs raise some questions about the possibility of exporting POF FBGs and the sensors based on them from the laboratory bench to the mass production market.

The possibility of arbitrary design of fiber Bragg gratings and the very short time required to write the gratings make the point-by-point grating writing technique very interesting and would appear to be able to fill this technological gap. On the other end this technique is hardly applicable for microstructured fibers because of the writing beam being scattered by the air-holes. We report on the design and realization of a microstructured polymer optical fiber made of PMMA for direct writing of FBGs. The fiber was designed specifically to avoid obstruction of the writing beam by air-holes. The realized fiber has been used to point-by-point write a 5 mm long fourth order FBG with a Bragg wavelength of 1518 nm. The grating was inspected under Differential Interferometric Contrast microscope and the reflection spectrum was measured. This is, to the best of our knowledge, the first FBGs written into a mPOF with the point-by-point technique and also the fastest ever written into a polymer optical fiber, with less than 2.5 seconds needed.

8426-43, Session 9

An intrinsic biochemical concentration sensor using a polymer optical fibre Bragg grating

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A new type of fibre-optic biochemical concentration sensor based on a polymer optical fibre Bragg grating (POFBG) is proposed. The wavelength of the POFBG varies as a function of analyte concentration. The feasibility of this sensing concept is demonstrated by a saline concentration sensor.

When polymer fibre based on poly(methyl methacrylate) is placed in water a differential hydraulic pressure is generated by the water concentration difference inside and outside the fibre. This differential hydraulic pressure drives the water into the polymer fibre, leading to a fully swollen fibre and a maximum wavelength increase of the POFBG. If solute exists in the water the process of osmosis takes place in this water-fibre system. An osmotic pressure which is proportional to the solution concentration, will apply to the fibre in addition to the hydraulic pressure. It tends to drive the water content out of the fibre and into the surrounding solution. When the surrounding solution concentration increases the osmotic pressure increases to drive the water content out of the fibre, consequently increasing the differential hydraulic pressure and reducing POFBG wavelength. This process will stop once there is a balance between the osmotic pressure and the differential hydraulic pressure. Similarly when the solution concentration decreases the osmotic pressure decreases, leading to a dominant differential hydraulic pressure which drives the water into the fibre till a new pressure balance is established. Therefore the water content in the polymer fibre - and consequently the POFBG wavelength - depends directly on the solution concentration.

A POFBG wavelength change of 0.9 nm was measured for saline concentration varying from 0 to 22%. For a wavelength interrogation system with a resolution of 1 pm, a measurement of solution concentration of 0.03% can be expected.

8426-44, Session 9

An investigation into the wavelength stability of polymer optical fibre Bragg gratings

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The inscription of Bragg gratings has been demonstrated in PMMA-based polymer optical fibre. The water affinity of PMMA can introduce significant wavelength change in a polymer optical fibre Bragg grating (POFBG) and this feature has been used successfully for humidity sensing. In polymer optical fibre losses are much higher than with silica fibre. Apart from the extrinsic loss associated with structural imperfections, there are intrinsic losses in polymer optical fibre due to either absorption by the constituent material or Rayleigh scattering. Very strong absorption bands related to higher harmonics of vibrations

of the C-H bond dominate throughout the visible and near infrared. Molecular vibration in substances generates heat, which is referred to as the thermal effect of molecular vibration. This means that a large part of the absorption of optical energy in those spectral bands will convert into thermal energy, which eventually drives water content out of the polymer fibre and reduces the Bragg wavelength of the grating inscribed in the fibre. In this work we have investigated the wavelength stability of POFBGs in different circumstances. The experiment has shown that the characteristic wavelength of a POFBG starts decreasing after a light source is applied to it. This decrease continues until an equilibrium inside the fibre is established, depending on the initial water content inside the fibre, the surrounding humidity, the optical power applied, the fibre size and the precise composition of the fibre. Our investigation has shown that POFBGs operating at around 850 nm show much smaller wavelength reduction, and shorter equilibrium time than those operating at around 1550 nm in the same fibre; POFBGs with a smaller diameter show similar advantages over those with a larger diameter; POFBGs operating in a very dry environment are least affected by this thermal effect.

8426-45, Session 9

Microstructured plastic optical fibers for applications in FTTH systems

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Continuous development of information and communication technologies, observed during last decade has resulted in evolution of telecommunication systems into optically transparent networks, with optical fibers carrying information directly to the user premises. This, in turn, resulted in significant development of novel types of optical fibers, supporting broadband transmission both in core and access networks. Although in the core network there is no alternative for single mode silica fibers, the specific requirements of local area networks (especially intra-building installations) may privilege the application of other types of optical fibers, like multi mode silica or large core plastic optical fibers (POFs). These latter, offering the advantages of mechanical flexibility together with low cost of manufacturing and simplicity of installation, seem to be specifically interesting in the context of intra-building systems and, therefore, are continuously considered as an interesting alternative in local area networks, particularly in FTTx systems.

It seems that the main limiting factors for common application of polymer fibers in various transmission systems are relatively high attenuation and, what is even more critical in intra-building systems, high values of modal dispersion resulted from large diameters of typical POF cores. It seems that both problems could be possibly overcome by application of microstructured design of the fibers. In particular - proper design of fiber geometry and periodicity of its microstructure allows introduction of photonic band gaps which would result in favorable low-loss propagation conditions in POF structures with air core (but at the cost of far more complicated installation). The microstructured design should also allow significant lowering of modal dispersion or even single mode operation in POFs with large dielectric core and lowering of their macro-bending sensitiveness, as well. Ultimately, proposed solution should enable significant improvement of transmission parameters, than those achievable in presently available POF structures.

This work is focused on the selected aspects of designing of microstructured POF (mPOF) with relatively large core, limited modal dispersion and improved resistance to bending losses, discussed in the context of its possible application in FTTH systems. The calculations confirmed the possibility of effective controlling both the propagation and macro-bending losses, as well as manipulation on the number of modes and modal area. The careful theoretical analysis allowed to design a series of geometries supporting the propagation of limited number of modes and, simultaneously, relatively large mode area and limited bending losses. The recently developed design with geometry considered as optimal supports propagation of only 3 modes, enables modal area of 260µm2 and bending losses less than 1dB/turn for 1 cm bend. The first technological attempts to manufacturing the designed mPOFs are in progress and, hopefully, will be reported during the conference together with the experimental results verifying theoretical predictions.

8427-01, Session 1

High resolution microscopy using line confocal structured illumination

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No abstract available

8427-02, Session 1

Patterned illumination for analysing neuronal function in 3D

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We demonstrate simultaneous patterned illumination to perform 3D multisite nonlinear photostimulation to analyse neuronal function. Using holographic projection of multiple foci in 3D, we describe a means to extend synaptic integration studies to the entire dendritic tree. Our setup includes a two-photon fluorescence microscope for rendering the 3D structure from which the stimulation sites are chosen. To project the multiple stimulation foci at various locations within the neuron's dendritic tree, we spatially encode a phase-hologram on an incident near-infrared femtosecond-pulse Ti:S laser via a programmable spatial light modulator. The projected foci bring about highly localized two-photon uncaging of neurotransmitters. We used the technique to analyse neuronal response in 300µm thick slices of rat somatosensory cortex. We performed whole-cell recordings of layer II pyramidal cells, which were initially stained with fluorescein for 3D imaging. Caged (MNI-) glutamate was released from an electrode close to the cell at a constant pressure. Glutamate-induced currents were found to vary quadratically with power, characteristic of two-photon uncaging. The lateral and axial resolutions of uncaging based on laser power setting and pulse-widths (5-10ms) were 3.9 and 4.1µm (half-widths), respectively. We performed simultaneous uncaging at multiple sites on different dendrites extending into different planes and observed summation at synaptic inputs onto shafts. This technique allows simultaneous uncaging at multiple 3D-locations on dendritic trees. The holographic generation of any desired spatial light pattern offers unprecedented flexibility in designing input patterns for synaptic integration studies.

8427-03, Session 1

Estimation of single cell volume from 3D confocal images using automatic data processing

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Cardiac myocytes are highly structured cells with a non-uniform morphology. Precise determination of their volume is essential to understand many aspects of cardiac physiology, including the correct evaluation of hypertrophic changes of the heart. Despite this fact, simple and unified techniques that allow determination of the single cardiomyocyte volume with sufficient precision are still limited. Here, we describe a novel analytical approach to assess the cell volume from confocal microscopy images and its modifications when the size of living cardiomyocytes is evaluated. Instead of the currently used empirical approach, we propose to use an analytical procedure, based on the analysis of cumulative frequency distribution intensity histograms obtained by the computational rendering of 3-D confocal images. We found that the inflex point of the first derivation of this curve where the second derivation converges to zero can easily be recognized and used to estimate the actual cardiomyocyte volume. Our data showed that this technique is independent on the laser gain and/or pinhole settings and is also applicable on images of cardiac cells stained with low fluorescence markers, such as cytoplasmic probes (calcium indicators), or endogenously fluorescent molecules (NAD(P)H or flavins), while taking in consideration morphological non-uniformities of each cardiac cell. Volumes thus determined are compared to those obtained by conventional geometrical calculations in cells from Wistar, as well as in spontaneously hypertensive rats (SHR), during growth from 10 to 20 weeks. We are convinced that this approach presents a promising new tool for investigation of changes the cardiomyocyte volume and structure during normal, as well as pathological cardiac growth. Supported by Integrated Initiative of European Laser Infrastructures LaserLab Europe II (EC's Seventh Framework Programme FP7/2007-2013 under grant agreement n° 228334) and the Research grant agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic VEGA No. 1/0296/11.

8427-05, Session 1

New imaging technique using degree of polarization for the study of polarimetric properties for non-invasive biomedical diagnostic

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This work is the presentation of a new imaging technique which enables near real time simultaneous multispectral acquisition of the so called "Degree Of Polarization" (DOP) in polarimetry, the normalized difference between two intensities of perpendicular polarization states, exploiting CCD RGB cameras. It is used as the contrast element to study the optical properties of a medium and to determine the difference for light propagation in turbid media for different polarization input.

In this sense, it may be described according to the matrix formalism proposed by Jones and Mueller, which is the classical polarimetric approach to study jointly several polarimetric properties (i.e. diattenuation, retardance and depolarization). Traditionally this approach is well known considering linear and/or circular polarizations, but beyond that the new improved method also permits the acquisition of DOP for all the possible elliptic ones.

This is realized employing an incoherent input white light beam whose polarization is changed without perturbing the system since, using nematic liquid crystals variable retarders (LCVR) opportunely calibrated, no mechanical tools are necessary.

Additionally, the interest of doing multispectral imaging is relevant because it allows to consider different deeps of penetration. In fact this technique is just superficial, since just the photons which has scattered only once or twice from the superficial tissue contribute to the image.

It will be demonstrated that the elliptical DOP degenerate in the linear and circular ones, furthermore the direct acquisition of a complete set of RGB images as function of phase and polarization of the incident beam considering a continuous dynamical variation of just one control parameter of the only non-mechanical used instrument: the applied voltage on LCVR.

Thus the dynamical evolution monitoring of the light-matter complex interaction is merely obtained as function of beam ellipticity and polarization just with the remote control via computer of only one parameter and through the appropriate trick in post-data processing. Particularly this last one corresponds to elaborate each single CCD color image with its CCD color homologous in term of LCVR retardance, even if for that color the voltage to apply is different. The advantages of this

kind of process are evident for this purpose and the memory needed for storage and ensuing data processing.

Moreover media characteristics will be enhanced structural difference otherwise often indistinguishable with naked eye and classical imaging method, e.g. sane vs pathologic tissue, in order to allow minimally invasive optical diagnostic. Besides, since no type of sample preparation is necessary, i.e. tissue biopsy, radiation or contrast agent injection, the system is a perfect candidate for a new imaging system considering in-vivo and ex-vivo non-invasive diagnostic medical application.

Thus the biomedical application of this method suggests a simple, direct, fast and also easily exploitable future employment, as a desirable mean for clinical investigation but also for digital recognition in biometrics.

Further new elements to improve the model of light scattering and matter-light interaction will be acquired, in particular considering a very complete characterization of the system response using latex microspheres suspension to simulate turbid media with different concentration.

8427-103, Session 1

Endo-microscope for early carcinoma diagnosis

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To address the need for a reliable early-stage detection and treatment method of carcinoma in epithelial tissues, we are developing an endoscopic microscope compatible with conventional clinical practices. The device is firstly envisaged to be capable of conducting large area, deep tissue imaging with sub-cellular resolution, in order to deliver histo-pathology analogous tissue insights necessary to distinguish disease from healthy tissue; and secondly, providing a precise laser resection and destruction of cells identified as potentially malignant, to directly eliminate even the smallest carcinoma spots, which with conventional methods remain invisible.

Non-linear, multi-photon fluorescence imaging has proven its benefits as the method of choice for deep tissue imaging in neuroscience research and has recently been explored for endoscopic applications in medicine. Fluorescent, molecular imaging agents currently developed for medical applications have already delivered highly promising results for early-stage tumour detection.

Using femtosecond lasers necessary for non-linear microscopy opens up avenues to two additional, important applications that can be realised in parallel: label-free imaging based on hyperspectral autofluorescence and second-harmonic generation; and laser ablation with sub-cellular precision. The label-free imaging is highly relevant for clinical use, as it avoids the non-trivial step of tissue staining. Precise microscopic laser destruction of malignant tissue could enable a “search & destroy” approach for very early-stage carcinoma, thus avoiding more invasive surgical interventions at later stages of tumour development.

8427-06, Session 2

Spectral imaging microendoscopy in ducts and vessels

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A fiber microendoscope of 0.5-1.3 mm diameter providing up to 30000 pixel resolution in white light and fluorescence imaging mode has been developed and tested on biophantoms, mammary ducts and blood vessels ex vivo. Cancer lesion has been detected as a patch surrounded by the adjacent healthy tissue in breast ducts. Images and video will be provided. The studies were conducted in cooperation with Fibertech (Japan) and Polydiagnost GmbH (Germany).

8427-07, Session 2

High-resolution fluorescence imaging of whole brains with confocal ultramicroscopy

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Light-sheet based microscopy (ultramicroscopy), coupled with optical tissue clearing, has been recently proposed (Dodt et al. Nat Met 2007) to reconstruct whole mouse brains with microscopic resolution. In this technique the sample is illuminated by a sheet of light and the fluorescence is observed from an axis perpendicular to the illumination plane.

This approach seems well-suited for high resolution whole brain imaging because it allows optical sectioning in a wide-field architecture assuring frame rates more than 2 order of magnitude higher than those of optical point-scanning techniques or electron microscopy. Moreover, this technique doesn’t require mechanical slicing of the specimen, which can introduce problems of layer misalignment and surface matching.

However, ultramicroscopy is limited because of residual scattering inside cleared tissues, which expands the excitation light sheet and blurs the collected fluorescence images, preventing whole brain imaging with high contrast and microscopic resolution.

To overcome this limitation several methods have been proposed, such as structured illumination (Kalchmair et al. Opt Lett 2010), but all these strategies share the same drawback, i.e. long acquisition times, as many images has to be acquired to produce a single final one.

We developed a novel technique (confocal ultramicroscopy, conf-u) in which out-of-focus and fluorescence light is rejected by a spatial filter. Conf-u combines light-sheet illumination with a confocal detection scheme, allowing high-contrast imaging while maintaining the high frame rates characteristic of ultramicroscopy.

We compared our technique with structured illumination, showing significant improvements both in terms of contrast enhancement and frame rate. To demonstrate the capabilities of our conf-u, we reconstructed the complete spatial distribution of Purkinje neurons throughout the cerebellum and we traced mm-long neuronal projections across a mouse brain.

8427-08, Session 2

Self-interference digital holographic microscopy for live cell imaging

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Quantitative digital holographic multi-focus phase imaging enables label-free minimally invasive live cell analysis by high resolution detection of sample induced optical path length changes. However, a drawback of many experimental arrangements for the analysis of living cells with digital holography is the requirement for a separate reference wave which results in a phase stability decrease and the demand for a precise adjustment of the intensity ratio between object and reference wave. Thus, a self interference digital holographic microscopy (DHM) approach was explored which only requires a single object illumination wave [1]. Due to the Michelson interferometer design of the proposed experimental setup two wave fronts with an almost identical curvature are superimposed. This results in a simplified evaluation of the digital holograms by spatial phase shifting reconstruction [2,3] and Fourier transformation-based spatial filtering [4]. In addition, an efficient application of methods for the reduction of coherent noise is enabled. It is demonstrated that the use of low cost laser light sources with a short coherence length in the experimental setup is possible and that the proposed method can be integrated in common research microscopes. Results from comparative investigations to a modular DHM system with a fiber optic reference wave [5] demonstrate that an up to five times increased temporal phase stability is achieved. The applicability of the proposed self interference principle is illustrated by data from the topography and refractive index data of technical specimens and living single cells. This includes results from resolution test charts, optical fibers and micro particles. Furthermore, adherent and suspended cancer cells have been investigated in Petri dishes during migration and analyzed for morphology changes in perfusion chambers due to flow and osmotic stimulation. In summary, the method prospects to be a versatile tool for quantitative phase imaging as simplification is important for the establishment of these methods in live cell analysis.

References

[1] B. Kemper, A. Vollmer, C. Rommel, J. Schnekenburger, G. von Bally, "Simplified approach for quantitative digital holographic quantitative phase contrast imaging of living cells", J. Biomed. Opt. 16, 026014 (2011).

[2] D. Carl, B. Kemper, G. Wernicke, and G. von Bally, "Parameter optimized digital holographic microscope for high-resolution living cell analysis," Appl. Opt. 43, 6536-6544 (2004).

[3] B. Kemper, D. Carl, J. Schnekenburger, I. Bredebusch, M. Schäfer, W. Domschke, and G. von Bally, "Investigation of living pancreas tumor cells by digital holographic microscopy," J. Biomed. Opt. 11, 034005 (2006).

[4] C. J. Mann, L. F. Yu, C. M. Lo, and M. K. Kim, "High-resolution quantitative phase contrast microscopy by digital holography," Opt. Express 13, 8693-8698 (2005).

[5] B. Kemper, D. Carl, A. Höink, G. von Bally, I. Bredebusch, J. Schnekenburger, "Modular digital holographic microscopy system for marker free quantitative phase contrast imaging of living cells," Proc. SPIE 6191, 61910T (2006).

8427-09, Session 2

Three-dimensional digital holographic tracking of optically manipulated particles for the inner analysis of living cancer cells

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The uncontrolled growth of abnormal cells and their migration toward adjoining tissues and organs is influenced by the micromechanical properties of the cytoskeleton. Thus, a key challenge is to develop new methods in order to obtain information about the inner mechanical properties of cells. Numerous works have been focused on the biomechanical cellular properties. However, most these methods observe the whole cell, the cell surface or are limited to the two-dimensional analysis of manipulated intracellular structures or internalized particles. Here we present a novel method to study inner cell properties by 3D manipulation and 3D tracking of internalized particles in living cancer cells. For this purpose, a holographic optical tweezers (HOT) [1] system that enables three dimensional optical manipulations and self interference digital holographic microscopy (DHM) [2] which provides 3D tracking [3] were combined in a single workstation. Results from investigations on cancer cells show that the high precision three-dimensional manipulation of particles in cells by HOT together with accurate DHM-based three-tracking and quantitative phase imaging provides new possibilities to study the intracellular morphology.

[1] F. Hoerner, M. Woerdemann, St. Mueller , B. Maier, C. Denz, Full 3D translational and rotational optical control of multiple rod-shaped bacteria J. Biophoton. 3, 468-475 (2010).

[2] B. Kemper, A. Vollmer, C. Rommel, J. Schnekenburger, G. von Bally, "Simplified approach for quantitative digital holographic quantitative phase contrast imaging of living cells", J. Biomed. Opt. 16, 026014 (2011).

[3] P. Langehanenberg, G. von Bally, B. Kemper, "Autofocussing in Digital Holographic Microscopy", 3D Res. 2, 01004 (2011).

8427-10, Session 2

Quantitative measurement of absolute cell volume and intracellular integral refractive index (RI) with dual-wavelength digital holographic microscopy (DHM)

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Quantitative Phase Imaging techniques including DHM have been applied recently in the field of cell imaging to monitor and quantify non-invasively dynamic cellular processes modifying cell morphology and/or content. Concretely, the DHM phase signal is highly sensitive to cell thickness and intracellular integral RI variations associated with transmembrane water movements.

As net water flow across the cell membrane leads at the same time to changes in cell thickness and intracellular RI, the interpretation of phase signal variations remains difficult. To overcome this drawback, we have developed a Dual-wavelength Digital Holographic Microscopy (DHM) setup that allows to separately measure, with a single CCD camera acquisition, thickness and integral RI of living cells. The method is based on the use of an absorbing dye that enhances the refractive index dispersion of the extracellular medium. Practically, two significantly different phase signals can be obtained when measuring at two appropriate wavelengths.

The dual wavelength hologram is acquired in an off-axis configuration, where the off-axis angle between object and reference wave is carefully adjusted for each wavelength. The spectral content of each object wave can then be filtered individually in the Fourier space of the dual wavelength hologram and two phase images can be reconstructed.

Having measured the two phase images and the RI of the extracellular solution at the two wavelength, one can then solve for the unknown parameters intracellular RI and cell thickness for each pixel in the image. These parameters allow to deduce other important biophysical parameters of living cells including absolute cell volume, dry mass concentration and water membrane permeability.

8427-11, Session 3

Membrane permeable luminescent metal complexes for cellular imaging

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Luminescent dye molecules capable of passive cell delivery may be used as molecular probes across cellular imaging, cell biology, molecular biology, microbiology, and flow cytometry applications. The majority of probes used in cellular imaging are fluorescent and based on organic, typically polyaromatic, chromophores. The short luminescence lifetimes of such species, typically <10 ns, limits their environmental sensitivity, e.g., towards molecular oxygen, and their application for fluorescent lifetime imaging (FLIM). Ruthenium polypyridyl complexes have unique photophysical properties which make them potentially invaluable as probes for cellular imaging. These include long lived and polarised luminescence, good photostability, long emission wavelengths and large stokes shifts. However, there has been a longstanding barrier to their exploitation in this context as such complexes do not typically passively diffuse across the cell membrane.

In this contribution, recent work by our group developing novel families of luminescent ruthenium and iridium peptide conjugates will be described.

Results from live cell imaging demonstrate that the peptide can be tailored to facilitate effective transmembrane transport of the dye and to target specific cells or cell organelles. However, our results also indicate that the nature of the metal and its counter-ligands play an important role in targetting and membrane transport.

The complexes, because of their large Stokes shifts can, uniquely, be used simultaneously for resonance Raman and luminescence cellular imaging. We present examples of peptide conjugates that exhibit an oxygen or membrane sensitive luminescence and resonance Raman spectroscopy which can can be used to determine the probes distribution in the cell. We propose that such complexes may find application in multiplexed analysis of the cell environment.

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References

[1] U. Neugeburger, Y. Pellegrin, N. Moran, W. Signac, RJ Forster, T E. Keyes, Chem Comm. 2008, 5307

[2] L. Cosgrave, U. Neugebauer, R.J. Forster, T.E. Keyes, Chem Comm, 2010, 46, 103.

8427-12, Session 3

Optoacoustic platform for noninvasive accurate monitoring of multiple physiologic parameters

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Noninvasive devices that could quickly provide continuous, accurate monitoring of multiple physiologic parameters in both high acuity and low acuity environments would greatly facilitate prompt recognition and treatment of a variety of life-threatening illnesses. Our goal is to improve the patient care by developing a multiparameter, noninvasive, optoacoustic diagnostic platform that will accurately and continuously measure cerebral and central venous oxygenation (oxyhemoglobin saturation), total hemoglobin concentration, cardiac output, circulating blood volume, cardiac index, systemic oxygen delivery, hepatic function, and other important physiologic parameters. At present, invasive measurements (requiring blood sampling and/or blood vessel catheterization) of these parameters are routinely used in the care of large populations of patients including patients with traumatic brain injury, critically ill patients, patients with circulatory shock, anemic patients, surgical patients. The optoacoustic technique can also be used for noninvasive measurement of blood pressure in vessels: arteries, arterioles, veins, and capillaries. We proposed and built optoacoustic systems operating in a wide near IR spectral range from 680 to 1064 nm for monitoring of these parameters and performed animal and clinical tests of the systems. Our systems include highly-portable, light-weight, inexpensive, laser diode-based systems suitable for clinical applications. We developed patient interfaces that incorporate highly-sensitive, wide-band (25 kHz - 10 MHz) optoacoustic probes specifically designed and built for these diagnostic applications. The systems were tested and calibrated in in vitro and in in vivo studies in large animals using catheterization, blood sampling, and measurements of blood parameters in the samples with a “gold standard” CO-Oximeter. Then we tested the systems in several clinical studies on continuous and intermittent measurements of cerebral venous blood oxygenation, central venous blood oxygenation, peripheral venous blood oxygenation, and total hemoglobin concentration. Our animal and clinical data indicate that the accuracy of the optoacoustic measurements is approaching that of “gold standard” invasive techniques.

8427-13, Session 3

Micoring resonator arrays for multiparameter biochemical analysis

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Modern biochemical analysis often requires advanced multiparameter approaches in order to fulfil the needs for high sensitivity and specificity at the same time.

Integrated optical microring resonator (MRR) sensors enable label-free analyte detection with high sensitivity and fast response rate. Such devices can be realised at reasonable cost thanks to full-wafer fabrication techniques. Furthermore, arrays of individually functionalized microring resonators are highly promising for applications in multiparamteter analysis due to their small footprint. Different functional binding sites promote the accumulation of different target molecules on individual MRR. The binding of target molecules to the MRR surface results in an increase of the MRR resonance frequencies which can be measured with high accuracy.

We have recently demonstrated a particularly economic approach to analyze large arrays of MRR-sensor elements coupled to a single bus waveguide. In order to measure the response of the individual MRR from the array to external stimuli, we employ a special frequency modulation scheme in which each MRR is independently modulated and phase sensitive lock-in detection is used to filter the respective frequency component from the superimposed complex transmission spectrum of the bus waveguide.

We fabricated test arrays comprising up to 12 MRR coupled to a single bus waveguide. A silicon nitride based material system was chosen to realize the devices. Each element of an array was integrated with a platinum heater electrode for thermo-optical modulation. A tunable laser system was used for optical characterization and a clear readout of the individual MRR resonance frequencies was possible by employing the modulation scheme above.

With our first results, we point out the large potential for multiplexed label-free detection of diverse bio molecular compounds. Due to the miniaturization of the multisensor arrays the realization of portable sensor systems will be feasible.

8427-14, Session 3

Resonant dielectric nanostructures for biosensor applications

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In the last decade, many technologies based on electrochemistry, enzymatic, fluorescence, and novel materials have been developed for the fabrication of highly sensitive biosensors [1-2]. Fluorescence detection techniques are probably the most used in this field but it remains a great challenge to detect fluorescent targets with the lowest detection threshold and best sensitivity, which is critical in early diagnostics and therapies [3-4]. On the other hand, the relatively high cost of the detection and the fabrication of the materials limit their practical applications. The goal of our study is to make novel bio-array substrates which use concentrated optical near-fields with remarkably enhanced field intensity by means of integrated periodic nanostructures [5-6]. Beside the sensitivity enhancement in comparison to commonly used chips, the new substrate is fabricated by using low-cost materials achieved by innovative nano-structuring procedures.

In this work, we report the fabrication of low cost materials such as SiO_2 and ZnO nanopillar arrays and study of their electromagnetic resonance behavior for field-induced fluorescence enhancement and their application in the optical biosensing technology. To study the strong field intensity enhancement, several optical and geometric parameters

of ZnO and SiO2 periodic nanopillars were systematically varied and manufactured via innovative lithographic and replication processes. Reproducible high quality nanostructures can also be obtained for different structural parameters (i.e. periods, diameters and heights) on transparent glass slides coated with a thin layer of Indium Tin Oxide (ITO).

Given this challenge, the surface of the structures has been modified in order to enhance the quantity and favour the adhesion of the labeled antibody on the nanopillars. A process has been recently developed consisting of the silanization of the surface for introducing functional amino groups. The activation of the amino silanized sensors is achieved with glutaraldehyde, a cross linker with the ability to covalently bind the biomolecules. A fluorescence measurement technique has been designed and built to characterize the optical properties of the manufactured samples. The primary advantage of this system is the ability to modify the incident excitation angle which is a crucial parameter for determination of the resonant angle. The measurements have shown a strong fluorescence enhancement and will be described in detail.

For the optimization of the experimental work it is essential to theoretically analyze dielectric nanorod structures, in detail in three dimensions before fabrication. Such calculations are very difficult when using commercially available tools. We have thus employed an in-house developed code (hades3d), allowing accurate calculations of 3D nanostructures with reasonable computing time. With this code based on the finite element method (FEM), a detailed 3-dimensional optical properties of dielectric nanorods were obtained. All in all, experimental and computational results show strong fluorescence enhancement, which may contribute to develop more efficient and sensitive biosensors.

[1] Y. Zhao, X. Zhao, Z. Gu, Adv. Funct. Mater. 20, (2010) 2970.

[2] I. L. Medintz, H. T. Uyeda, H. Mattoussl, Nat. Mater. 4, (2005), 435.

[3] C. Oillic, P. Mur, F. Vinet, T. Billon, Biosens. Bioelectron, 22, (2007), 2086.

[4] W. Hu, Y. Liu, Z. Zhu, H. Yang, C. Li, ACS Appl. Mater. Interfaces. 2, (2010), 1569.

[5] D. Neuschaefer, W. Budach, C. Wanke, and S. Chibout, Biosens. Bioelectron 18, (2003), 489.

[6] A. Selle, C. Kappel, M. A. Bader, G. Marowsky, K. Winkler, U. Alexiev, Opt. Lett. 30, (

8427-15, Session 3

Addressable LED arrays for biophotonics applications

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We present the design, fabrication and packaging of addressable 16x16 micro-LED array chips, and the use of a CMOS/micro-LED stimulator unit in an optogenetic neural stimulation set-up. The individual light emitters on the array are 20µm in diameter, and the array has a 150µm pitch. A unique feature of the emitters is that they are surrounded by parabolic reflectors. This enhances the light extraction efficiency, and results in a directional light beam emerging from the transparent substrate. It also reduces the amount of cross-talk between neighbouring pixels. For the packaging, we present a flip-chip packaging technology that is compatible with a standard aluminium bond pad finish on the CMOS chip that addresses the micro-LED array. To optimise the yield of the flip-chip packaging process, we developed a simple evaluation method that allows us to assess quickly how many of the 256 individual bonds are making proper contact. This evaluation method is also being used in attempts to reduce the pitch size from 150µm downwards. We expect that this pitch can be reduced to less than 75µm with this flip-chip assembly technology. The material from which the arrays are made is gallium nitride, and the emission wavelengths that can be covered with this materials system are: 390-530nm. We report the latest results from a fully packaged CMOS-gallium nitride stimulator unit that is used to stimulate neurons which have been photosensitised with channelrhodopsin.

8427-16, Session 4

Lasing from biological cells expressing green fluorescent protein

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Since their invention, lasers have revolutionized the processing of materials, enabled or significantly improved a vast variety of measurement techniques, and became an integral part in data storage and communication devices. At the same time, lasers remain at the focus of industrial development and fundamental research. Particular attention has been paid to making smaller, more powerful, and more efficient lasers and to generating shorter laser pulses. Although lasers and the coherent light they emit are omnipresent today, lasing has remained a man-made phenomenon. Lasers are non-existent in nature and in particular laser light has not been observed in biological materials or living organisms.

Here, we present a new type of laser that is based on the biologically produced green fluorescent protein, GFP, and show that single live cells expressing GFP can form the optical gain medium of a laser [1,2]. Besides the fundamental significance of being able to generate laser light in a biological system, we expect that these bio-lasers will also become enabling tools for imaging and tracking of biological processes.

Following transfection of mammalian cells with vectors encoding for expression of eGFP, cells were filled into a micro-cavity and pumped with ns pulses of blue light. We found that single cells can produce laser light at sub-nJ pump thresholds. Interestingly, these single cell lasers generate complex spatial emission patterns that are associated with their transversal mode structure and contain information about cell morphology and size.

We will also present currently unpublished results on high-throughput analysis of single cell lasers using a microfluidic cell-delivery platform (“lasing cytometer”). Here, the cells of a large population are one-by-one delivered to a micro-resonator and optically pumped with a low-cost diode. The output is recorded by an optically triggered fast detection system and statistically analyzed.

[1] M.C. Gather, S.H. Yun, “Stimulated emission from fluorescent proteins and single-cell biological lasers,” Nat. Photonics 5, 406 (2011).

[2] M.C. Gather, S.H. Yun, “Lasing from Escherichia coli bacteria genetically programmed to express green fluorescent protein,” Optics Letters 36, 3299 (2011).

8427-17, Session 4

Layered polymer: inorganic composite waveguides for biosensor applications

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In this work, we investigate the usability of layered polymer - inorganic composite waveguides for label-free sensing of surface bound bioreactions in an aqueous environment. The waveguide structure consists of a nanoimprint fabricated polymeric inverted rib waveguide with a sputtered Ta2O5 thin film on top. Microstructure studies indicate that the films were amorphous and very smooth being therefore suitable for integrated optical devices. Computational and experimental results indicate that Ta2O5 high-index coating on a polymer waveguide is an efficient configuration to manipulate the optical field profile of the guided mode. The interaction of the optical field with the surface is increased as a consequence of the mode profile localization near the surface, when high-index coating is deposited on a low-index waveguide. Young interferometer configuration with reference and sensors waveguide arms was utilized in sensor chips. Light from a laser source was

end-fire coupled into the chips and interference pattern produced by the outcoupled light was investigated. External µ-fluidic pump was utilized to produce analyte flow. Ambient refractive index change was characterized by applying DI-water with varying glucose concentration on waveguides. As a consequence, light propagating in the sensor arm experiences varying effective index, which is converted into a shift in interference pattern. With the waveguide length of 1 cm a detection limit in the order of 10^-7 refractive index unit (RIU) was achieved. Specific and unspecific binding reactions on the surface were investigated with C - reactive protein (CRP) and bovine serum albumin (BSA) molecules, respectively. Furthermore, negative control tests were carried out to confirm the specific binding phenomenon. Besides enhancing the sensitivity, inorganic high index coating was found to block effectively water absorption into the polymer structures. This was observed as a reduced transient drift in sensor response, when waveguides were exposed to water. Integration of nanoimprinted waveguides with capillary µfluidic channels is also discussed to produce integrated polymeric lab-on-a-chip platform.

8427-18, Session 4

Development of FBG probe for non-invasive carotid pressure waveform assessment

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The cardiovascular diseases have been widely reported as the largest cause of death in the world, namely ischemic, stroke and cerebrovascular diseases. One of the early indicators of cardiovascular diseases with growing interest is the arterial stiffness which is typically evaluated through the velocity and morphology of the arterial pressure wave.

In each cardiac cycle the heart generates a pressure wave which propagates through the arterial tree. Along its path, the pressure wave interacts with the arterial walls and, consequently, the morphology of a local arterial pressure wave can be assessed by the arterial distention movement, traditionally acquired with ultrasound systems. Due to its superficiality, proximity of the heart and high probability of atherosclerosis development, the carotid artery has particular interest to be monitored. The carotid pressure wave has four reference points: the Forward Wave, the Reflected Wave, the Dicrotic Notch and the Dicrotic Wave.

Comparing to traditional methods, fiber Bragg grating (FBG) based sensors can offer many advantages, namely, compactness, immunity to electromagnetic interference, high sensitivity, low noise and immunity to light source intensity (Othonos, 1999). A non-invasive FBG probe for the acquisition of the arterial distention wave will be presented. It consists in a small box crossed by an optical fibre with a FBG in the middle. Below the FBG there is a sphere that can moves in the vertical direction. During the data acquisition, the sensor is placed in the skin portion above the carotid artery, allowing the motion of the sphere with the arterial distention movements. In this way, the strain on the FBG, induced by the sphere movement, will follow the arterial distention pattern.

Preliminary results will be presented for the acquisition of the carotid distention wave in a healthy young human carotid artery, with an acquisition rate of 950 Hz. A clear distinction of the four standard reference points of the carotid pulse waveform will be shown. The analysis of preliminary data point toward a promising probe to the acquisition of the carotid distention waveform.

8427-19, Session 4

A minimally invasive chip based near infrared sensor for continuous glucose monitoring

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Assessment of glycaemia in diabetes is crucially important for prevention of both, acute and long term complications. Continuous glucose monitoring (CGM) is certainly the most appropriate way for optimizing the glycaemic control, since it prevents or delays the progression of complications associated with hypo- or hyperglycaemic events, reducing morbidity, mortality, and overall costs in health care systems. In this paper we describe the concept and first in vitro results of a minimally invasive, chip-based NIR-Sensor for continuous glucose monitoring. The sensor concept is based on difference infrared absorption spectroscopy, which was evaluated within laboratory measurements of D+-Glucose dissolved in water. The laboratory measurements revealed a linear relationship between glucose concentration and the integrated difference spectroscopy signal with a coefficient of determination of 99.6% in the physiological concentration range of 0-500 mg/dL. Suitable wavelength bands were identified in which the correlation is preserved and commercial light sources are available for realisation of a spectrometer-less, integrated NIR-sensor. In the designed sensor the component area (non-disposable) is separated from the detection area (disposable, low-cost). The disposable part of the sensor is fluidically connected to a micro-dialyses needle, accessing glucose subcutaneously via the ISF (interstitial fluid) or intravascularly. The non-disposable part contains all the optical elements, like LED´s and photo-detectors. The disposable part has been designed as a polymer chip favorably made of a cyclo olefin copolymer (COC). The in- and out-coupling of the optical signal is achieved across the plane of the chip by using total internal reflection on mirrors integrated into the fluidic chip. Optical simulation of this design showed, that up to about 27% of the light emitted by the LED can be transmitted through the reference and sample detector channels, respectively. The glucose is continuously measured by considering the difference signals of light at the corresponding wavelengths, as a function of time or in defined intervals if the light sources are operated in pulsed mode. The in-vitro measurements show an absolute error of about 5 mg/dL with a relative error of 5% for glucose concentrations larger than 50 mg/dL and about 12 % in the hypoglycemic range (<50 mg /dL)

8427-20, Session 4

Photoplethysmography system for blood pulsation detection in unloaded arterial conditions

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In this study, we demonstrate innovative photoplethysmography (PPG) measurement system which can provide unloaded arterial wall conditions during data recording for correct and reliable assessment of conduit circulatory bed. We affirm that the PPG measurements in balanced transmural arterial pressure conditions might serve as the reference for the PPG method unification. It is a step forward toward the standardization of the PPG methodology, and shows the PPG pulsation waveform dependence on the applied probe contact force. The system includes a PPG amplifier, custom made arterial PPG probes, adjustable probe fastenings, and firmware with integrated pulsation waveform analysis algorithm for real-time arterial wall distension assessment. The probe contact force influence on the pulse waveform is characterized by several parameters derived from results of the current pilot study. Certain criteria are proposed to determine the optimal probe contact force that ensures repeatable measurement conditions crucial for consequent PPG waveform analysis.

8427-21, Session 5

Application of laser tweezers Raman spectroscopy techniques to the monitoring of single cell response to stimuli

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We will describe our techniques and experiments to monitor cell dynamics via Raman Spectroscopy on Laser-Trapped in vitro cells. In particular we study the effects of laser trapping on the cells as well as the exposure to pharmaceuticals, in particular those associated with chemotherapeutics. We will show that our techniques can be used to study the life cycle of cells and their apoptosis following exposure to tumor killing drugs.

8427-22, Session 5

Rotational behaviour of rod-shaped self-propelled bacteria investigated utilising holographic optical tweezers

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Flagellated bacteria feature one of the smallest known rotational motors, which drives the flagella and allows the bacterial cell to propel actively through its environment. The biophysical properties of this kind of motors are not yet fully understood and even less is known about the role of hydrodynamic interactions of multiple motors, including possible cooperative effects and the resulting spatio-temporal dynamics. Utilising the great versatility of sophisticated holographic optical tweezers [1,2] we realise defined states of single and multiple bacterial cells, thus inducing the whole range from simple to complex interaction scenarios. Interactions can be investigated in three-dimensional arrangements of optically trapped bacteria [3] and in optically induced two-dimensional arrangements of surface-adhered bacteria. For the induction of defined configurations, we employ a precise positioning and orientation scheme which has been optimised for rod-shaped bacteria [3]. By means of structured, optically induced adherence at homogeneous surfaces, long-term monitoring without possible influences of the trapping laser is achieved. Digital image processing of video data with high temporal resolution allows us to access information on rotation frequencies and directions while observing optically trapped or surface-adhered bacterial cells. In the case of optically trapped bacteria there are a few studies that explore the rotation states of a single bacterial cell by means of tracking the position in a time-resolved manner with a position detection sensor [4,5]. While this approach is limited to single bacteria for fundamental reasons, the developed scheme based on image processing allows the simultaneous detection and measurement of multiple bacteria without any conceptional limits. In the case of surface-adhered bacteria we use a similar scheme, enabling the identification of the instantaneous bacterial body orientation of single and multiple bacterial cells. The possibility to monitor the behaviour of multiple bacteria simultaneously provides the potential to study their interaction and effects on their rotation behaviour directly. In this contribution we present our experimental platform for the investigation of bacterial rotational properties and discuss first, promising results.

[1] Woerdemann, M.; Gläsener, S.; Hörner, F.; Devaux, A.; Cola, L. D. & Denz, C. Dynamic and reversible organization of zeolite L crystals induced by holographic optical tweezers, Adv. Mater., 2010, 22, 4176-4179

[2] Hesseling, C.; Woerdemann, M.; Hermerschmidt, A. & Denz, C. Controlling ghost traps in holographic optical tweezers, Opt. Lett., 2011, 36, 3657-3659

[3] Hörner, F.; Woerdemann, M.; Müller, S.; Maier, B. & Denz, C. Full 3D translational and rotational optical control of multiple rod-shaped bacteria, J. Biophoton., 2010, 3, 468-475

[4] Rowe, A. D.; Leake, M. C.; Morgan, H. & Berry, R. M. Rapid rotation of micron and submicron dielectric particles measured using optical tweezers, J. Mod. Opt., 2003, 50, 1539-1554

[5] Min, T.; Mears, P.; Chubiz, L.; Rao, C.; Golding, I. & Chemla, Y. High-resolution, long-term characterization of bacterial motility using optical tweezers. Nat. Methods, 2009, 6, 831-835

8427-23, Session 5

Characterizing Matrigel stiffness by optical tweezers active microrheology

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Recent studies indicate how the cellular microenviroment plays a critical role in normal and pathological cell behavior. Cell proliferation, stem cell differentiation and tumor growth have been shown to be affected by substrate mechanical properties. In the field of tissue engineering, the mechanical characterization of the extracellular matrix (ECM) at the spatial scale of a single cell has become of great interest, as has the testing of mechanical hypothesis. While specialized hybrid synthetic-peptide materials allow the tuning of stiffness, the biological context of such systems is questionable. In contrast, our group has developed a simple method for tuning stiffness within naturally derived ECMs.

Matrigel is a commercial ECM used ubiquitously in 2D and 3D cell culture. It is a material of choice in stem cell studies and tumor biology as it promotes differentiation and migration of tumor cells. Here, we characterize Matrigel ECMs of different concentrations (30 - 100% 9.3mg/mL), under variable amounts of mechanical strain and temperature (20 and 37 °C) using optical tweezers based active microrheology (AMR). The mean values of stiffness (G') for the four concentrations were found to be between 20-120 Pa in the absence of strain. Matrigel polymerized within our strain gradient device exhibited stiffness ranging from 20 Pa to over 400 Pa within a single petri dish.

Interestingly, AFM and interferometry methods of measuring microscale stiffness, report values considerably higher than measured by bulk rheology. In contrast, our mean AMR values are consistent with bulk rheology and additionally reveal the spatial heterogeneity of Matrigel stiffness at the scale of a cell.

8427-24, Session 5

Mechanical properties of bleb formation during cell migration of primordial germ cells in zebrafish embryos

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Whereas the mechanisms controlling single-cell migration in vitro are relatively well understood, less is known concerning the mechanisms promoting the motility of individual cells in vivo [1]. In particular, it is not clear how cells that form blebs in their migration polarize to bring about movement in the context of the three-dimensional cellular environment. Understanding the means by which cells move within the tissue would benefit from determining the forces they exert on the environment and from evaluating the intracellular forces employed when moving the cell cytoplasm forward.

To this end, we have implemented holographic optical tweezers (HOT) [2] in an inverted fluorescence microscope to probe the mechanical properties of primordial germ cells (PGCs) of zebrafishes in vivo. While most HOT applications so far work in controlled in vitro systems [3,4], in vivo studies are challenging in the way that the environment is less defined. However, due to the ability to perform studies without mechanically disturbing the system HOT could become also a prominent technique for in vivo measurements. Thus calibrating and optimizing the system, we managed to probe PGCs that migrate in relatively deep locations, a few cell layers beneath the surface of the embryo. The

HOT setup will allow us to investigate the rigidity of the cell at multiple positions simultaneously, to analyse the spatial and temporal evolution and changes in this parameter during blebbing, and to evaluate the force generated by cytoplasmic streaming in the course of protrusion formation.

[1] Blaser et al., Developmental Cell 11, 613-627 (2006)

[2] Curtis et al., Optics Communications 207, 169-175 (2002)

[3] Akselrod et al., Biophysical Journal 91, 3465-3473 (2006)

[4] Hörner et al., Journal of Biophotonics 3, No. 7, 468-475 (2010)

8427-25, Session 5

Diagnostic of red blood cells viscoelastic properties by means of optical tweezers

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Viscoelastic characterization of cell is a crucial problem of understaning of tissue physiology. Methods probing the cellular viscoelastic properties provide tools to characterize the physiological state of the membrane and its changes caused by various diseases or drug effects. Optical tweezers technique is a powerful method for exploring problems related to quantitative characterization of objects at the micro scale. This technique is able to probe local properties of the trapped objects in aqueous solution having no impact from the bulk substrate and it is ideal for the study of cells in an natural environment. In the present work double-trap optical tweezers is suggested for studying viscoelastic properties of red blood cells (RBCs). Two optical traps are formed by two infrared laser (980 nm) beams focused by oil immersion objective. The position of one trap was controlled using acousto-optical deflector. In the experiment single erythrocyte was doubly trapped by both laser tweezers. The distance between the traps was 7.5 µm while erythrocytes were selected to be of 8 µm in size. One of the traps was stable while the second one was sinusoidally oscillating with an amplitude of 100 nm in the range of 0.1-10 kHz causing the displacements of the cell edges. Two extra lasers (635 nm and 670 nm) were focused on the RBC edges, the forward scattered light of these beams was detected using two quadrant photodiodes. Frequency dependence of the phase difference in the movement of the erythrocyte edges appeared to be highly dependent on the rigidity of the cellular membrane. Experimental observations showed that dependence of the phase shift between oscillations of the RBC opposite edges as a function of trap oscillations was qualitatively different for normal living RBCs and RBCs previously fixed by glutaraldehyde that makes the cells controllably rigid by cross-linking the proteins of the cell membrane. Dependence for fixed erythrocytes shifts to the right drastically indicating the increase of the cell stiffness. Thereby tweezers technique combined with an analysis of forced RBC edges motion allows quantitatively characterize the elastic properties of individual RBC membranes.

8427-26, Session 6

Towards gene therapy based on femtosecond optical transfection

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Gene therapy poses a great promise in treatment and prevention of a variety of diseases. However, crucial to studying and the development of this therapeutic approach is a reliable and efficient technique of gene and drug delivery into primary cell types. These cells, freshly derived from an organ or tissue, mimic more closely the in vivo state and present more physiologically relevant information compared to cultured cell lines. However, primary cells are known to be difficult to transfect and are typically transfected using viral methods, which are not only questionable in the context of an in vivo application but rely on time consuming vector construction and may also result in cell de-differentiation and loss of functionality. At the same time, well established non-viral methods do not guarantee satisfactory efficiency and viability. Recently, optical laser mediated poration of cell membrane has received interest as a viable gene and drug delivery technique. It has been shown to deliver a variety of biomolecules and genes into cultured mammalian cells; however, its applicability to primary cells remains to be proven. We demonstrate how optical transfection can be an enabling technique in research areas, such as neuropathic pain, neurodegenerative diseases, heart failure and immune or inflammatory-related diseases. Several primary cell types are used in this study, namely cardiomyocytes, dendritic cells, and neurons, but also MCF-10A cells which are important in breast cancer research. Preliminary studies suggest that optoinjection efficiency is dependent upon laser irradiation power and exposure time.As an example,femtosecond laser porationof primary dendritic cells show that up to ~45% of the irradiated cells were viably optoinjected using laser power of 87mW with 40 ms exposure time. We present our recent progress in optimising this technique's efficiency and post-treatment cell viability for these types of cells.

8427-27, Session 6

Noncontact microsurgery and micromanipulation of living cells with combined system femtosecond laser scalpel-optical tweezers

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We report on the results of using self-developed multifunctional combined laser system consisting of a femtosecond laser scalpel (Cr:Forsterite seed oscillator and a regenerative amplifier, 620 nm, 100 fs, 10 Hz) and an optical tweezers (cw laser, 1064 nm) for performing noninvasive microsurgical and micromanipulation procedures on living cells. Femtosecond lasers offer numerous advantages over long-pulse lasers and can be successfully used in biological studies, as they provide ultrahigh spatial and temporal resolution. The proposed combined system was employed to address topical biomedical problem, namely embryo biopsy. Embryo biopsy is actively used for preimplantation genetic diagnosis of monogenic diseases or chromosomal aberrations. In contrast with mechanical or semi-mechanical techniques of embryo biopsy we present the results of fully contactless laser-mediated polar body (PB) and trophectoderm (TE) biopsy of early mammalian embryos. To perform a PB biopsy the fs laser scalpel was initially used to drill an opening in the zona pellucida, and then the PB was extracted out of the zygote with the optical tweezers. Unlike PB biopsy, TE biopsy allows diagnosing maternally-derived as well as paternally-derived defects. Moreover, as multiple TE cells can be taken from the embryo, more reliable diagnosis can be done. TE biopsy was performed by applying laser pulses to dissect the desired amount of TE cells that had just left the zona pellucida during the hatching process. Optical tweezers were then used to trap and move the dissected TE cells in a prescribed way. Laser power of 50-70 mW in optical tweezers was enough to manipulate the cells. In both cases the energy of fs laser pulses was thoroughly optimized (20-35 nJ per pulse at the target) to prevent cell damage and obtain high viability rates. Morphological and fluorescent analysis (fluorescent dyes Hoechst 33258 (Sigma, B-2261) and Propidium iodide (Invitrogen, P1304MP) were used) showed that laser-based biopsy did not compromise further in vitro embryo development(survival rates were higher than 80%).In conclusion, the proposed techniques of laser-based embryo biopsy enable accurate, contamination-free, simple and quick microprocessing of living cells.

8427-28, Session 6

Photonic crystal cavities for resonant evanescent field trapping of single bacteria

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In monitoring the quality of drinking water with respect to the presence of hazardous bacteria, there is a strong need for on-line sensors that allow quick identification of bacterium species at low cost. In this respect, combining photonics and microfluidics is promising for lab-on-a-chip sensing. Photonic crystals (PhCs) have proven to form a versatile platform for controlling the flow of light and creating resonant cavities on a sub-wavelength scale. The goal of our research is to use PhC cavities for optical trapping and Raman-sensing of microorganisms in water, exploiting the evanescent field of the cavity resonance for these functionalities.

In this work we focus on the optical trapping aspect. Three types of cavities (H0, H1 and L3) in a hole type PhC are simulated for their suitability for trapping bacteria in water. First, in 3D FDTD simulations, the cavities are optimized with respect to Qr by tailoring the shape, position and size of the (surrounding) holes of the cavities. The trapping-induced resonance shift is determined by studying the effect of the bacterium index distribution in close proximity of the cavity. The total Q-factor is then limited by introducing coupling (Q//), facilitating transmission measurements and meeting the resonance shift requirement (shift<FWHM). This leads to Qtot=1170, 2000 and 3300 for respectively the H0, H1 and L3 cavity. The photonic crystals are fabricated in silicon-on-insulator, by e-beam lithography and dry-etching. Finally the fluidic channel is created on top of the crystal, using a dry-film resist. Trapping experiments are performed by exciting the cavity at the resonance frequency, while 1 µm polystyrene beads, used as force probes, are streaming across the cavity in a steady flow. Optical trapping events are recorded with a microscope from top, demonstrating optical trapping for several photonic crystal cavities. Current work involves trapping experiments with bacteria.

8427-29, Session 6

Towards a laser-integrated module for marker-free sorting of micrometer-sized particles in microfluidic channels

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In recent years, microfluidic devices have become important tools for cell analysis in biology and medicine. They enable fast and inexpensive analysis with reduced consumption of analytes. The combination of both optical detection and optical manipulation forms a compact biomedical system on a single chip. However, optical detection in combination with fluorescence-activated cell sorting often requires sample preparation by attaching an antibody-labeled fluorochrome to the cell. Such fluorochromes might affect cell viability and function. Marker-free optical detection triggering a subsequent optical sorting process provides an attractive alternative to typical analysis concepts with the need for optical markers.

The presented approach utilizes VCSEL (vertical-cavity surface-emitting laser) -based devices for both the optical detection and the optical sorting in microfluidic channels with Y-junctions. The analyzing unit consists of a solitary VCSEL with an extended resonator. The external mirror is formed by a high-reflection coated concave surface on top of the microfluidic channel. Particles in the microchannel flow through the resonator and induce a change of the cavity resonance. Such a sensitive detection principle allows the triggering of a subsequent sorting process. A pattern of several arrays of optical traps forms the sorting unit, exploiting the working principle of the optical lattice. Particles passing the lattice are stepwise attracted by each optical trapping beam. By using a separate switching of the laser arrays, the particles can be selectively deflected into each branch of the microfluidic Y-junction.

We present the design, fabrication, and properties of the above VCSEL devices, including the highly reflecting dielectric coating of the external mirror. We integrate both devices as well as structured heat sinks with the microfluidic chip, which corresponds to a high degree of miniaturization. As a next step, detection and sorting experiments with the fabricated laser-based unit will be shown.

8427-30, Session 6

Optical trapping detects colored noise in the fluctuations of an extended DNA molecule

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Study of the dynamics of the stretched states of a single DNA molecules is important because different processes (as translation, transcription or replication) need the loss of the quaternary structure.

We studied fluctuations of an optically trapped bead connected to a single DNA molecule anchored between the bead and a cover glass. In our case, and at difference with the previous publications, the stiffness of the tweezers is of the same order of magnitude of the DNA stiffness. By means of forward scattered light, the position of the optically trapped bead is recorded at acquisition rate of 50 kHz.

Power spectral densities of the bead position for different extensions of the molecule were compared with the power spectral density of the position fluctuations of the same bead without the molecule attached, comparing the experimental results with the previous results. The DNA stiffness is calculated considering to be stationary the extra noise and solving the Fokker Planck equation.

Experiments showed that the fluctuations of the DNA molecule extended up to 80% of total length by a force of 3 pN include the colored noise contribution with spectral dependence f-a, with a=0.8. These fluctuations introduce new terms in the description of the system beyond the stiffness of the polymer and can be understood as a reorganization of the energy storing of the biomolecule.

The experiment was repeated by anchoring the DNA between two optically trapped beads. In this case, one of the traps has a stiffness around ten time bigger than the other. Again the colored noise component was observed in the fluctuations of the probe bead.

8427-31, Session 7

Linear and nonlinear imaging of electrical activity and morphology in intact tissues

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Correlations between morphology of connections and functionality, such as electrical activity, is one the of the major issue in neuroscience and cardiology in the comprehensions of many pathologies and mechanisms of behaviour and computation.

Nowadays, there are several imaging techniques which offer a complementary approach to visualize intact networks in tissues. Each of those offer a complementary approach and furnish different informations on the role of network components.

In this seminar, we will concentrate our attention on linear and non linear laser imaging modalities capable to obtain 3D tomographic reconstruictions containing both functional and morphological informations.

It will be presented mainly three main examples of applications centered on the measurents of plasticity, action potential propagation and whole organ imaging.

Experimental results obtained on these arguments will be presented , together with the description of the imaging techniques developed in our lab.

8427-32, Session 7

Polarization-modulated SHG analysis of the thermal modification of corneal stroma

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The fibrillar order of certain connective tissues is critical for their biological function, as it is the case for the corneal stroma and its peculiar refractive properties. However the inter- and intra-fibrillar relationships behind this orderly architecture may become modified under e.g. pathological conditions, accidental traumas, etc.. An interesting example is the thermal treatment of the cornea, as it is performed in its laser bonding during e.g. penetrating keratoplasty. Laser bonding proves superior to conventional suturing, especially when temperature is kept within 50-60°C. In this range it was reported functional fibrils misalignment and tissue adhesion, without collateral impairment of intra-fibrillar relationships such as collagen denaturation. Indeed collagen denaturation begins above 60°C and may significantly obstruct the post-op recovery. Unfortunately the identification of ideal conditions, which is just below the onset of collagen denaturation, is hardly possible on visual inspection.

Here we propose the use of second harmonic generation (SHG) microscopy to investigate both the inter- and intra-fibrillar configuration of connective tissues with a regular architecture. Polarization-modulated SHG micrographs of corneal specimens treated at different temperatures were analyzed by an extension of the theoretical models from the recent literature. This extension holds potential for a complete three dimensional retrieval of the fibrils orientations and accounts for both the effective misalignment and inner conformation of the collagen molecules which contribute to the SHG signal. Finally we discuss issues and future perspectives before the use of this approach for clinical applications.

8427-33, Session 7

Two-photon autofluorescent and second-harmonic generation microscopy for the tracking of TiO2 and ZnO nanoparticles penetration into human tooth in vitro

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Penetration of nanoparticles into tooth tissue is of significant interest in solving the problems related to the reduction of tooth sensitivity, enamel strengthening and restoration and cosmetic bleaching. Particles of TiO2 and ZnO are known for their photoactive properties and can be used as bacteria inhibitors. Monitoring of particles penetration into tooth is, however, a challenging task.

In this work, the two-photon autofluorescent (AF) and second-harmonic generation (SHG) microscopy for visualization of penetration of TiO2 (1 µm in size) and ZnO (200 nm in size) nanoparticles into tooth tissue was demonstrated. Tooth tissue slices containing dentin and enamel sections were used as samples. Evidence of TiO2 and ZnO nanoparticles penetration into dentin and enamel of human tooth was observed using multiphoton tomography (MPM) operating in the superficial tissue area down to 200 µm. In this study, AF and SHG images of the enamel and dentin were obtained.

We have found that the enamel produces a strong AF signal, clearly revealing the structure of the enamel rods. Dentin produces both AF and SHG signals. The collagen of the dentin tubules gives a strong SHG signal, while the peritubular dentin responds with both the SHG and AF signals.

The present data show that ZnO nanoparticles penetrated up to a depth of 45 µm, the maximum penetration depth of TiO2 nanoparticles was 5 µm. Size and shape of nanoparticles as well as their aggregation ability play a significant role in the penetration process. ZnO nanoparticles in contrast to TiO2 produce a strong SHG signal, because they possess considerable second-order nonlinear optical coefficients (d333 and d311) due to their crystalline symmetry.

Our results demonstrate the effectiveness of using MPM to visualize the tooth structure and nanoparticles penetration.

8427-34, Session 7

Non-invasive label-free investigation and typing of head and neck cancers by multimodal nonlinear microscopy

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Early detection and typing of tumors is of utmost importance for prognosis and successful treatment. Currently, staining is the golden standard in histopathology but requires surgical removal of tissue. In order to avoid resection of non-diseased tissue and to guide the surgeon during surgery a non-invasive real-time imaging method is required.

In this contribution a combination of second harmonic generation (SHG), two photon excited fluorescence (TPEF) and coherent anti-Stokes Raman (CARS) imaging has been employed to investigate tissue sections of head and neck carcinomas focussing on laryngeal carcinoma. Primary laryngeal and other head and neck carcinomas consist to 99% of squamous cell carcinoma. By fusing the various imaging methods it is possible to measure the thickness of the epithelial cell layer as a marker for dysplastic or cancerous tissue degradation and to differentiate keratinizing and nonkeratininzing squamous cell carcinomas (SCC). Due to the correlation of nonkeratinizing SCCs with a human papillomavirus (HPV) infection as a subentity of head and neck cancer, which is associated with a better clinical prognosis, this finding is of high diagnostic value. TPEF is capable of displaying cell nuclei, therefore, morphologic information as cell density, cell to cytoplasm ratio, size and shape of cell nuclei can be obtained by this method. SHG selectively visualizes the collagen matrix of the connective tissue, which is useful for determination of tumor-islets boundaries within epithelial tissue - a prerequisite for precise resection. CARS in the CH-stretching region visualizes the lipid content of the tissue, which can be correlated with the dysplastic grade of the tissue.

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References

[1] C. Krafft et al., Analyst 134, 1046-1057 (2009).

[2] T. Meyer et al., Journal of Biomedical Optics 16, 21113, (2011).

[3] S.I. Pai et al., Annu. Rev. Pathol. Mech. Dis., 2009, 49-70 (2009).

8427-35, Session 7

Discrimination of skin diseases using the multimodal imaging approach

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Optical microspectroscopic tools reveal great potential for dermatologic diagnostics in the clinical day-to-day routine1-3. To enhance the diagnostic value of such nonlinear optical images obtained using isolated contrast mechanisms such as coherent anti-Stokes Raman scattering (CARS), second harmonic generation (SHG) or two-photon excited fluorescence (TPEF), the approach of multimodal imaging has recently been developed4,5. Here, we present an application of nonlinear optical multimodal imaging with Raman-scattering microscopy to a study of sizable human-tissue cross-sections. The samples investigated contain healthy tissue, keloid samples and various skin tumors.

This contribution details the rich information content, which can be obtained from the multimodal approach: While CARS microscopy, which - in contrast to spontaneous Raman-scattering microscopy - is not hampered by single-photon excited fluorescence, is used to monitor the lipid distribution in the samples SHG imaging selectively highlights the distribution of collagen structures within the tissue. This is due to the fact, that SHG is only generated in structures which lack inversion geometry. Finally TPEF reveals the distribution of autofluorophores within the tissue. The combination of these techniques, i.e. multimodal imaging, allows for recording chemical images of large-sized samples and - as this contribution will highlight - high clinically diagnostic value.

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1. K. König, H.G. Breunig, R. Bückle, M. Kellner-Höfer, M. Weinigel, E. Büttner, W. Sterry and J. Lademann, "Optical skin biopsies by clinical CARS and multiphoton fluorescence/SHG tomography", Laser Phys. Lett. 8, pp. 465-468, 2011.

2. X. Zhu, S. Zhuo, L. Zheng, K. Lu, X. Jiang, J. Chen and B. Lin, "Quantified characterization of human cutaneous normal scar using multiphoton microscopy", J. Biophoton. 3, 108-116, 2010.

3. R. Cicchi, S. Sestini, V. De Giorgi, D. Massi, T. Lotti and F. S. Pavone, "Nonlinear laser imaging of skin lesions", J. Biophoton. 1, 62-73, 2008.

4. N. Vogler, A. Medyukhina, I. Latka, S. Kemper, M. Böhm, B. Dietzek and J. Popp, "Optical skin biopsies by clinical CARS and multiphoton fluorescence/SHG tomography", Laser Phys. Lett. 8, 617-624, 2011.

5. N. Vogler, T. Meyer, D. Akimov, I. Latka, C. Krafft, N. Bendsoe, K. Svanberg, B. Dietzek, and J. Popp, "Multimodal imaging to study the morphochemistry of basal cell carcinoma", J. Biophoton. 3, 728-736, 2010.

8427-36, Session 8

Quantification and optimal control of contrast in CARS images

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Coherent anti-Stokes Raman-scattering (CARS) imaging has become an established tool in biophysics, biomedicine and chemistry.[1] Nonetheless, its application to visualize the distribution of low-molecular weight compounds such as drugs or metabolites in complex samples such as mammalian or plant tissue remains challenging.[2] This obstacle is central to be resolved in order to broaden the range of applicability of CARS microscopy, which is mostly restricted to visualization of the lipid content in biological samples due to the high density of CH-oscillators in lipids.[3]

This contribution reports on our recent approaches to quantify the CARS image contrast using microfluidic chips (as controlled and reproducible samples) in combination spatial-light modulators. One central aim is to determine the detection limit of model analytes in aqueous solutions by means of CARS image contrast and to quantify it.[4] Based on these experiments, the use of a spatial-light modulator in concert with self-learning algorithms is reported to optimally control the contrast of CARS images. In contrast to previous work, the experiments reported here use an image-contrast parameter for direct feedback in the self-learning algorithm. Thereby, conceptually novel experiments are discussed, which might have the potential to significantly broaden the applicability of CARS microscopy.

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References

[1] C. Krafft et al., Analyst 134, 1046 (2009).

[2] I. Weißflog et al., Plant Physiology 154, 604-610 (2010).

[3] J. P. Pezacki et al., Nat Chem Biol 7(3), 137-145 (2011).

[4] G. Bergner et al., Analyst 136, 3686-3693 (2011).

8427-37, Session 8

Force and Raman spectroscopy of single red blood cell

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There is great interest in the biophysics of red blood cells (RBC), both from a fundamental standpoint and in order to understand the role of various constituents in cell functioning and its mechanical and optical response.

In this work viscoelastic and spectroscopic properties of single RBC are probed using dual beam optical tweezers and Raman techniques, respectively. Complex response function of cell was measured by means of one and two particles passive microrheology at different stretching states yielding local and overall mechanical properties of exactly the same human erythrocyte. The frequency dependent response function (measured up to 10 kHz) was corrected for the presence of the traps and spectral distribution of complex stiffness over controlled range of cell deformation is calculated and discussed. The presence of non-thermal sources of membrane motions is also explored based on comparison of passive and active microrheology experiments. In order to get insight into structural changes of RBC due to deformation, Raman spectra of single cell were recorded. Evolution of Raman bands with cell deformation was analyzed using sensitive 2D correlation method. The combination of force and Raman spectroscopy is promising and potentially very powerful method to establish essential linkages between structure, mechanical properties and functions of living cells.

8427-38, Session 8

Use of Raman microspectroscopy to score the malignancy of breast cancer cells

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Although an altered metabolism is not the cause of malignancy, cancer cells cannot successfully elicit its malignant capabilities without the required metabolic transformation. Recent clinical and basic research studies have evidenced that up-regulation of fatty acids biosynthetic activity is a molecular event accompanying the pathogenesis and natural history of cancer disease. We hypothesize that the lipid content of breast cancer cells might be an indirect measurement of breast cancer progression. We have previously optimized a Raman microespectroscopy technique to analyze the lipidic content of breast cancer cells useful to explore the lipogenic phenotype associated to malignancy. In this study we used the MCF10A breast cell line, with a phenotypic plasticity for epithelial mesenchymal transition (EMT) according to the cell culture grown conditions, to analyse if lipidic metabolism was associated to the lost of epithelial characteristics. Raman spectra of MCF10A cells growing in confluent (epithelial characteristics) or sparse (mesenchymal characteristics) conditions were acquired with an InVia Raman microscope (Renishaw) with a backscattered configuration. The Raman excitation was performed with 514nm optical beam focused through a 60X objective and with power of 9mW. The spectra were background subtracted with a Labview programm and the gaussian fits for total fatty acids (TFA) and total unsaturated fatty acids (TUFA) bands (2853cm-1 and 3015cm-1 respectively) were performed in Matlab allowing the quantification of the two types of fatty acids in the cells. We used the principal component analysis (PCA) to assess the different profiling of their lipidic composition. SERS probes are under analysis to allow the identification of new metabolites (glutamate, lactate, etc...) associated to the EMT. These results might confirm that the Raman microspectroscopy is a useful tool to identify breast cancer cell aggressiveness.

8427-39, Session 8

Double optical fibre-probe device for the diagnosis of melanocytic lesions

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A double optical fiber-probe for combined Raman-fluorescence spectroscopy on human tissues was designed, developed, and tested on fresh skin biopsies. The developed device combines fluorescence spectroscopy with Raman spectroscopy in a tandem measurement via two distinct optical fibre-based probes, connected to the same detection system. Concerning fluorescence spectroscopy, the excitation is provided by two laser diodes emitting in the UV (378 nm) and in the visible (445 nm). These two source can be used to selectively excite fluorescence from NADH and FAD, which are among the brightest endogenous fluorophores in human tissues. For Raman and NIR spectroscopy, the excitation is provided by a third laser diode with 785 nm excitation wavelength. In both fluorescence and Raman, laser light is delivered to the tissue through the central optical fibre of a bundle. The surrounding 48 fibres of the bundle collect fluorescence and Raman on their distal end, while at their proximal they are shaped in a double line for optimal coupling with the spectrograph. Fluorescence and Raman spectra are acquired on a cooled CCD camera. The instrument has been tested and used on fresh human skin biopsies clinically diagnosed as malignant melanoma, melanocytic nevus, or healthy skin, finding an optimal correlation with the subsequent histological exam. In particular, we found that in the visible range (excitation at 378 nm and 445 nm) malignant melanoma has in average a fluorescence emission red-shifted with respect to the corresponding healthy tissue and nevi emission. Although this parameter can be used for diagnostic purposes, the sensitivity and specificity are still far from being good. A big improvement in terms of diagnostic sensitivity and specificity can be obtained by including in the analysis also Raman and NIR fluorescence emission. With the inclusion of Raman and NIR fluorescence spectroscopy we were able to diagnose malignant melanoma in a good agreement with common routine histology. With this study we demonstrated that the system can potentially contribute to improve clinical diagnostic capabilities and hence reduce the number of unnecessary biopsies in dermatology.

8427-40, Session 8

Detecting neuroinflammation non-invasively through the retina by means of Raman spectroscopy and multivariate analysis

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Retinal nervous tissue sustains substantial damage during the autoimmune inflammatory processes characteristic of Multiple Sclerosis (MS), and can be accessed non-surgically by Raman Spectroscopy, a non-invasive optical imaging technique. In this study we demonstrate the effectiveness of combining Raman spectroscopy with PCA (Principal component analysis) and PLS-DA (Partial least squares- discriminant analysis) to detect and monitor neuroinflamation in retina.

First, non-resonant near-infrared Raman spectroscopy was used to create a spectral library of eight pivotal biomolecules known to be involved in neuroinflammation; Nicotinamide Adenine Dinucliotide (NADH), Flavin Adenine Nucleotide (FAD), Lactate, Cytochrome C, Glutamate, N-Acetyl-Aspartate (NAA), Phosphotidylcholine, with Advanced Glycolization End Products (AGEs) analyzed as a reference. Glutamate, Lactate, NAA, NADH, and Phosphotidylcholine yielded strong peaks in solution and were chosen for further analysis. These five molecular spectra were used to tentatively characterize the Raman peaks of spectra taken in the ganglion cell layer of murine organotypic tissue.

The loading plots of the Principal Component Analysis (PCA) of 50 spectra taken of murine retinal tissue culture undergoing an inflammatory response and healthy controls were analyzed in order to characterize the molecular makeup of the inflammation. The loading plots revealed a heavy influence of peaks related to Glutamate, NAA, NADH, and Phosphotidylcholine to inflammation-related spectral changes. Partial Least Squares - Discriminant analysis (PLS-DA) was performed to create a multivariate classifier for the spectral diagnosis of neuroinflammed tissue, which was validated using venetian blinds w/6 splits. PLS-DA method yielded a diagnostic sensitivy of 100% and specificity of 100%. We demonstrate, then the effectiveness of combining Raman spectroscopy with PCA and PLS-DA statistical techniques to detect and monitor neuroinflamation in retina. With this technique we were able to detect Glutamate, NAA and NADH in retina tissue as signs for neuroinflammation.

8427-41, Session 9

Reusable silver plasmonic arrays for analytical applications

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Regular patterned metallized microstructured surfaces play an important role in advanced optical sensing applications. The strong electromagnetic field enhancement due to the excitation of localized and propagating surface plasmon polaritons is used for the effective enhancement of the inherent weak Raman signals which is known as surface enhanced Raman spectroscopy (SERS). Thus, fingerprint specificity will be combined with trace-level sensitivity makes SERS an attractive and powerful tool for analytical and bioanalytical applications [1].

Within this contribution the fabrication and application of reproducible SERS substrates is discussed in context to detection of low molecular weight substances like illegal dyes in spices. According to our previous works, we have established the electron-beam lithography (EBL) for fabrication of regular ordered gold nanostructures in order to achieve a reproducible signal enhancement [2-4]. Further, we addressed our works on fabrication techniques using a silver metal deposition on a pre-structured substrate [5]. Different preparation and material parameters has been fitted towards a more cost-efficient fabrication of simple, reproducible as well as reusable SERS substrates. Further, the selected surface modification of the SERS array with hydrophobic or hydrophilic layer is able to enrich analyte molecules like. The characterization by means of various optical and imaging techniques and the application towards an analytical detection scheme is introduced.

[1] K. K. Hering et al., Analytical and Bioanalytical Chemistry390, 113-124 (2008).

[2] D. Cialla et al., Analytical and Bioanalytical Chemistry394, 1811-1818 (2009).

[3] J. Petschulat et al., Optics Express18, 4184-4197 (2010).

[4] D. Cialla et al., ChemPhysChem11, 1918-1924 (2010).

[5] U. Hübner et al., Microelectronic Engineering88, 1761-1763 (2011).

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8427-42, Session 9

Application of innovative plasmonic nanostructures in (bio)analytics

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Silver and gold nanoparticles and nanostructured surfaces show unique optical properties in the visible and NIR spectral range. Due to the excitation of localized and propagating surface plasmon polaritons, respectively, these metallic nanostructures exhibit a strong local field enhancement, which is utilized e.g. to enhance the inherent small but molecular specific Raman cross section (surface enhanced Raman spectroscopy - SERS). [1] The SERS technique combines the requirements for a powerful technique applied to a multitude of analytical questions in chemical and biological analysis through fingerprint specifity as well as high sensitivity down to trace levels. Furthermore, the tip enhanced Raman spectroscopy (TERS) is created due to the combination of SERS with scanning probe microscopy (SPM) resulting in a spatial resolution down to the nanometer scale. [2]

Within this contribution, the application of anisotropic nanoparticles for the investigation on the emission enhancement in SERS is introduced. Here, the Raman scattered light experienced an enhancement due to plasmon resonances of the metallic nanoparticles. This emission enhancement phenomenon is investigated for different Raman bands of crystal violet by utilizing the anisotropic plasmonic character of gold nanorhomb SERS arrays. [3] Furthermore, the SERS and fluorescence readout application verfied by a DNA detection scheme using the same plasmonic arrays shows a great potential in bioanalytics. [4]

[1] Hering, K. et al. Analytical and Bioanalytical Chemistry 2008, 390, 113-124.

[2] Deckert-Gaudig, T. et al. Journal of Biophotonics 2008, 1, 377-389.

[3] Cialla, D. et al. ChemPhysChem 2010, 11, 1918-1924.

[4] Cialla, D. Weber, K. et al. Beilstein Journal of Nanotechnology 2011, 2, 501-508.

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8427-43, Session 9

Nanobiophotonics for molecular imaging of cancer markers: development of Epidermal Growth Factor receptor (EGFR) specific nanoprobes for Surface Enhanced Raman Spectroscopy (SERS)

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Our research aims to effectively image the Epidermal Growth Factor receptor (EGFR, HER1) distribution in cancers. Many cancers and pre-cancers over-produce the cell surface receptor EGFR. EGFR over-expressing A431 cancer cells and Normal Human Bronchial Epithelial cell controls are targeted through a biocompatible nanoprobe. This probe is formed by attaching modified EGF protein, an EGFR specific ligand, to 5, 20, or 45 nm diameter gold or silver nanoparticles (Au/AgNPs). By linking a molecule with the proper functional groups to the protein, EGF is altered to form stronger bonds to noble metals. The surface plasmon of aggregated metal nanoparticles is excited by using 632.8 nm or 785 nm laser wavelengths which leads to enhanced Raman spectra - referred to as surface enhanced Raman spectroscopy (SERS). Raman spectroscopy measurements of cells are obtained with a point-mapping scheme (0.3 μm step size) to chart the nanoparticle, and thus the EGFR, distribution. As EGFR is engulfed through endocytosis, we expect to visualize the aggregated nanoprobes in endosomes and lysosomes when using a confocal microscope for white light and Raman imaging. Our previous work using 632.8 nm laser excitation demonstrated signal to noise ratios of 850:1 at 1583 cm-1 and 7 orders of magnitude enhancement with 30 nm AuNPs tagged with anti-EGFR antibody incubated with A431 cells. Small EGF-coated nanoparticles should avoid an immune response. To test this hypothesis, mouse organs are harvested 24 hr. following tail vein injection to determine the nanoprobe biodistribution. The total organ metal (Au/Ag) content is assessed using Inductively Coupled Plasma - Mass Spectrometer (ICP-MS). We report our efforts to achieve SERS with small and large nanoprobes in cultured cells and assess the ability of these probes to avoid an immune response.

8427-45, Session 9

Application of cheap lasers in shifted excitation Raman difference spectroscopy

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Raman spectroscopy has increasing importance in a wide field of application particularly in real time monitoring of chemical processes, testing of food stuff, finding ingredients in unknown material mixture etc. Many materials of interest have resonance wavelength near to the excitation wavelength. Then we can take advantage of the resonant Raman spectroscopy. The disadvantage of this technology is the presence of a strong fluorescence background in the Raman spectrum. To suppress the fluorescence background we combine the mechanism of the resonant Raman spectroscopy with the shifted excitation Raman difference spectroscopy. In the paper the applicability of cheap green lasers for this purpose and their tunability by temperature and current is investigated.

Our setup consists of two pigtailed lasers at a wavelength of 532 nm with a small wavelength difference switched by a fiber switch with a frequency up to 50 Hz. Every switching pulse triggers an optical spectrometer to measure the backscattered light. After subtraction of the two different spectra we obtain a resonant Raman spectrum with a minimized fluorescence background. The specific wavelengths of the two lasers were set by thermal tuning. To verify the setup the Raman spectra of Isopropanol and Tetrachlormethan have been measured.

8427-46, Session 9

Characterization of atherosclerotic plaque depositions in vivo by fiber optic Raman spectroscopy and ex vivo by FTIR imaging

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Visualization as well as characterization of inner arterial plaque depositions is of vital diagnostic interest, especially for the early recognition of vulnerable plaques. Established clinical techniques provide valuable visual information, but can not deliver information about the chemical composition of individual plaques. Here, we employ Raman-probe spectroscopy to characterize the plaque compositions of arterial walls on a rabbit model in vivo. Rabbits were treated with a cholesterol enriched diet. The combination of Raman and infrared spectroscopy with conventional light microscopy enables analyzing the biochemical composition of atherosclerotic plaques without markers in a non-destructive way. Thin sections were prepared and studied in transmission mode using a FTIR imaging spectrometer with a 64 64 focal plane array detector (Agilent, USA). For data analysis and image reconstruction multivariate algorithms such as vertex component analysis (VCA) were applied. The individual plaque components were spectroscopically identified. The IR and Raman spectra indicate variations in the composition of these plaques. Furthermore, spectroscopic imaging shows the plaque distribution and compositions in a more quantitative manner than traditional staining techniques. The results are in good agreement with the histopathology and demonstrate how IR and Raman spectroscopy can complement standard histopathologic tools.

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8427-47, Session 10

Monitoring in vivo treatment response with structural and functional optical coherence tomography

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Optical coherence tomography (OCT) provides detailed microstructural and microvascular tissue images in-vivo. In addition to its obvious role for early disease detection and diagnosis, it can also be used to guide, optimize and personalize treatments. We have thus used OCT and its vascular-imaging extensions (Doppler, speckle-variance) to image treatment response in tumor-bearing animal models. Specifically, we have explored treatment-induced tissue changes during and following photodynamic therapy (PDT) and radiation therapy (RT). Both cellular and vascular tissue compartments have been followed longitudinally for up to 3 weeks following treatment delivery. Selected histological validation was used to determine biological endpoints and to help interpret the OCT findings. Results from the PDT and RT studies will be presented, including alterations in the tumor microvasculature and changes in the spatial and temporal features of OCT speckle. Implications for OCT-based early treatment assessment / guidance / feedback, with potential for therapy improvement and optimization, will be also discussed.

8427-48, Session 10

High-speed polarization-sensitive OCT at 1060 nm using a Fourier domain mode-locked swept source

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Optical coherence tomography (OCT) in the 1060 nm range is interesting for in vivo imaging of the human posterior eye segment (retina, choroid, sclera). Water absorption is considerably lower than in the 1300 nm band, and compared to 800 nm, weaker scattering and low absorption by the retinal pigment epithelium enables deeper penetration into the choroid and the sclera. As an addition to structural images, polarization-sensitive OCT (PS-OCT) can reveal the presence of birefringent or depolarizing structures, or map the optical axis orientation within the sample. In retinal imaging, these additional data can be used for more precise delineation of different layers. With a state-of-the-art high-speed swept source, such as a Fourier domain mode-locked (FDML) laser, densely sampled 3D dataset covering a wide field of view can be acquired within a few seconds with minimal impact of motion artifacts.

We implemented a two-channel PS-OCT system with balanced detection and demonstrated imaging in the 1060 nm range with an FDML laser with 175 kHz sweep rate (bidirectional). With a new broadband semiconductor optical amplifier (SOA) as gain medium, the laser can sweep over a total range greater than 90 nm with a center wavelength between 1065 and 1070 nm. The laser spectrum coincides thus with the local water absorption minimum, making it ideal for retinal imaging. By modulating the SOA current during a wavelength sweep, we can optimize the output spectrum and thereby improve the depth resolution by 25% down to 9 µm in air (6.5 µm, resp., in tissue). The output power is symmetric for both sweep directions, hence an OCT A-scan rate of 350 kHz could be possible without further modification of the light source (i.e. without buffering of the laser output). Preliminary PS-OCT images (structure, retardation, optical axis orientation) acquired with the laser show high contrast between the retinal layers and a strong signal from choroid and sclera. We are currently preparing the imaging system for wide-field 3D-image acquisition.

8427-49, Session 10

Guiding glaucoma laser surgery using Fourier-domain optical coherence tomography at 1.3 µm

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Glaucoma is an eye disease that can gradually lead to total blindness if not treated on time. It is the second cause of blindness worldwide with 80 to 105 million people affected by the disease and approximately 6 million people are blind due to glaucoma. The standard clinical treatment for glaucoma starts with drug administration and is usually followed by surgery. Due to post surgical complications like wound healing process, this standard method has a success rate of 50% globally. As femtosecond laser cutting is effective in volume and does not involve wound healing process, glaucoma laser surgery could be a novel technique to supplement the existing incisional glaucoma surgery. The ability of Optical Coherence Tomography (OCT) to produce non-invasive high resolution tomographic images in real-time has drawn much attention towards biomedical applications, mainly in ophthalmology for imaging the retina and the anterior segment of the eye. In this paper, we present the development and utilization of OCT for monitoring the glaucoma surgery performed with a femtosecond laser at 1.65 µm wavelength. We have used two Fourier-domain OCT systems: a commercial Swept-Source OCT (SS-OCT) and a laboratory Spectral-Domain OCT (SD-OCT) with improved spatial resolution. Both systems operate at 1.3 µm center wavelength and enable the visualization of the Schlemm's canal, the principal site where the surgery has to be done. The light source for the SD-OCT system consists of two spectrally shifted and fiber-coupled superluminescent diodes so that the effective FWHM bandwidth of the source is 200 nm with an output power of 10 mW. The spatial resolution of the SD-OCT system is 6 µm × 12 µm (axial × transverse) and the dynamic range is greater than 70 dB. Cross-sectional images and video of Schlemm's canal surgery obtained from both commercial and laboratory systems are presented and compared.

8427-50, Session 10

Snapshot retinal imaging with multi-MHz FDML OCT

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Most optical coherence tomography (OCT) systems used for retinal imaging today operate only at up to 100kHz axial scan rate. Since the probability for involuntary eye movements increases with the total duration of the imaging procedure, the achievable dataset size is limited unless active eye tracking is used. Hence the total field of view is restricted to rather small areas under the requirement of sufficiently dense sampling. While these small areas are sufficient for many applications, full fundus coverage has several important benefits. These include co-registration and comparison with established imaging modalities such as fundus photography, which cover a far larger field than OCT devices. Moreover, the acquisition of a densely and isotropically sampled dataset allows for the reconstruction of arbitrary scan paths in post-processing, similar to what is known as curved multiplanar reformation (cMPR) in computed tomography.

For retinal imaging, snapshot-like acquisition times of well below 1s are necessary for a high probability that the 3D datasets do not contain microsaccades. We analyzed 54 datasets acquired at 684kHz and 1.37MHz axial line rate, and a significant number of these datasets is distorted by eye movements. The mean saccadic frequency was found to be ~0.3Hz in accordance with the literature. Hence, to achieve a full and densely sampled coverage of the human ocular fundus, (multi-) MHz line rates are necessary. Additionally, functional imaging such as Doppler OCT relies on ultra dense sampling and benefits from short time intervals between adjacent scans. Finally, for video-rate 3D OCT the volume rate should be (by definition) larger than about 20Hz. Even for small volumes of 2562 axial scans this requirement results in >1.3MHz scan rate.

Here, we report on progress in retinal imaging using Fourier-domain mode locked (FDML) lasers, which operate at multi-MHz line rates for snapshot-like ultrawide-field OCT imaging. Wide-field 3D OCT datasets consisting of two million axial OCT scans of the human retina are acquired in 0.3s, shorter than the mean intersaccadic interval. This performance is achieved with an Yb co-pumped, buffered FDML laser source operating at 1050nm. A two-beam setup doubles the 3.35MHz OCT line rate to 6.7MHz, which is 16x faster than any non-FDML source used for retinal OCT. The dataset size is 3168x705 at 6.7MHz axial scan rate. The "snapshot" acquisition time already offers a high probability of undistorted datasets. Moreover, even if eye movements occur, now the scan rate is high enough to directly correct even the fastest saccades without loss of information. For slow systems, saccades move much faster than the slow axis of the beam scanners, such that an uncorrectable gap may be found in the dataset. However, for fast enough systems, the spot movement is faster than saccade speed. Thus the distortion that is produced per frame can be corrected in post-processing. We will discuss correction approaches that benefit from axial scan rates provided by FDML lasers and we will analyze saccade frequency in multi-MHz OCT datasets.

8427-51, Session 10

Extended range MHz FDML laser for OCT imaging of the anterior segment

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Optical coherence tomography (OCT) using Fourier domain detection (FD-OCT) offers both a sensitivity advantage over time domain OCT as well as dramatically higher imaging speeds. However, in contrast to time domain OCT, all FD-OCT systems suffer from sensitivity degradation over imaging depth. This effect is well-known as sensitivity roll-off and affects both swept-source (SS-OCT/OFDI) as well as spectrometer-based systems.

Today, some of the fastest OCT systems are based on swept-source technology and apply FDML lasers. Systems with up to 5.2MHz line rates (per imaging spot) were demonstrated. However, these systems exhibit a quite steep sensitivity roll-off of 4.5mm imaging depth or 0.75mm/dB. This z6db roll-off point corresponds to a coherence length of >9mm, an improvement of more than a factor of 2 over previous MHz FDML lasers. This was accomplished by reduction of the dispersion in the FDML cavity by means of a broadband dispersion compensation module (DCM). The DCM incorporates two chirped fiber Bragg gratings (FBG) designed to correct both normal and anomalous dispersion around 1310 nm.

We demonstrate OCT imaging of the anterior segment of the human eye at 1.6MHz scan rate. At the maximum sampling rate of 1.5GS/s provided by our data acquisition, the effective detection bandwidth is limited to ~0.7GHz, representing the bottleneck in our OCT system. However, scan range and imaging depth can be traded off by adjusting the sweep range: To acquire 3D datasets of the whole anterior chamber the laser sweep range was reduced to 60nm to provide sufficient imaging range of ~6mm. For zoomed in high-definition OCT data sets of the cornea, anterior chamber and the trabecular meshwork, the tuning range was increased to >100nm to reach a measured axial resolution of 15µm in air. The system acquires data sets with ~1000 x 1000 axial scans in merely 0.8s.

8427-52, Session 11

Comparative analysis of optical coherence tomography signal and microhardness for demineralization evaluation of human tooth enamel

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The diagnosis of dental caries at an early stage enables the implementation of conservative treatments based on dental preservation, avoiding surgical and restorative procedures. Several diagnostic methods have been developed for detection of incipient caries. Methods like visual-tactile and radiographyc feature are the most commons in the clinical practice but are limited for this application. The Optical Coherence Tomography is a technique that provides information on optical properties of enamel, which may change due to the decay process.

The objective of this study was to evaluate the ability of OCT to detect different stages of demineralization of tooth enamel during the development of artificial caries lesions, taking as a reference standard for comparison sectional microhardness testing.

Different stages of caries lesions were simulated using the pH cycling model suggested Feathestone et al. and modified by Argenta et al. (2003). The samples were exposed to 0 (control group), 5, 10, 15, 20 and 25 days at a daily regimen of three hours demineralization followed by remineralization during 20 hours. It was used an OCT system with superluminescent LED at 930nm with 2mW of power. Images of 4000x1500 microns (2000x512 pixels) were generated in all the lession region.

The results obtained from the OCT technique presented similar behavior to microhardness, except for the group 25 days, due to inability to perform indentations reading in areas of more intense demineralization.

A linear relationship was observed between the OCT and microhardness techniques for detection of demineralization in enamel. This relationship will allow the use of OCT technique in quantitative assessment of mineral loss. The OCT technique has shown promise for the evaluation of incipient caries lesions. Because it uses only light in his analysis, is non-invasive allowing its use in vivo and in real time.

8427-53, Session 11

Phase and amplitude optimization in an optical coherence tomography system using a programmable spectral filter

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We demonstrate the use of a fully-integrated programmable optical spectral filter to compensate all orders of chromatic dispersion in an all-fibre Fourier-domain (FD) optical coherence tomography (OCT) system. In our experiment, performed at 1550 nm, the point-spread-function of the OCT system, originally 58 µm wide, asymmetric, and with strong sidelobes, is successfully made symmetric and recompressed to 38 µm, close to the theoretical limit of 36 µm. Note that here the resolution was limited by the bandwidth of our programmable spectral filter, a Finisar WaveShaper, but models with twice more bandwidth are already on the market. Our experiment clearly demonstrates however that a programmable optical spectral filter (or spectral pulse-shaper) can be a very powerful tool for OCT. Because the spectral pulse-shaper is fully programmable, we can compensate for chromatic dispersion of any origin at any order, including average sample dispersion or the dispersion of any optical element present in the setup. If the setup is reconfigured or if a different sample is introduced, it only takes a few seconds to reprogram the filter. Adding a linear phase ramp to the filter, we have also demonstrated that we can also take advantage of the Fourier shift theorem, and shift the point where the optical path difference is zero, which can be quite important for FD-OCT. Finally, we have made experiments to not only filter the spectral phase but also the spectral amplitude of the light. In this way, it was possible to simultaneously compensate dispersion and give the spectrum a Gaussian shape. Accordingly, the amplitude filter allows for an improvement of the signal-to-noise ratio while simultaneously using the WaveShaper as a phase filter optimizes the OCT system resolution.

8427-54, Session 11

Processing optical coherence tomography data as a synthetic digital hologram for transverse resolution improvement

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The problem of restoration Optical Coherence Tomography (OCT) images, acquired with tightly focused probing beam, in out-of-focus region for improving lateral resolution of the OCT has been considered. Phase stability issue has been discussed and phase equalization algorithm has been proposed. The similarity between data acquisition in OCT and Digital Holography was also shown. After phase equalization, the algorithm of digital refocusing, based on some methods from the DH, have been applied to the simulated as well as to experimental OCT data, acquired with tightly focused scanning beam to shift the focal region. From several images with different focal region position, obtained by digital refocusing, the image with micrometer lateral resolution in the whole investigated volume has been fused.

8427-55, Session 11

Fabrication of high quality optical coherence tomography (OCT) calibration artefacts using femtosecond inscription

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Optical coherence tomography (OCT) is a non-invasive three-dimensional imaging system that is capable of producing high resolution in-vivo images. OCT is approved for use in clinical trials in Japan, USA and Europe. For OCT to be used effectively in a clinical diagnosis, a method of standardisation is required to assess the performance across different systems. This standardisation can be implemented using highly accurate and reproducible artefacts for calibrating both at installation and throughout the system lifetime. Femtosecond lasers can write highly reproducible and highly localised micro-structured calibration artefacts within a transparent media. We report on the fabrication of high quality OCT calibration artefacts in fused silica using a femtosecond laser. The calibration artefacts were written in fused silica due to its high purity and ability to withstand high energy femtosecond pulses. An Amplitude Systemes s-Pulse Yb:YAG femtosecond laser with an operating wavelength of 1026 nm was used to inscribe three dimensional patterns within the highly optically transmissive substrate. Four unique patterns have been designed to measure various parameters, including the points spread function (PSF), sensitivity and distortion - key parameters which define the performance of the OCT. The calibration artefacts have been characterised using an optical microscope equipped with a quantitative phase microscope (QPm) and trialled on two different OCT systems operating with different parameters. The performance of these two OCT systems have been evaluated using these artefacts. The results demonstrate that the femtosecond inscribed artefacts can be used to quantitatively and qualitatively validate the performance of any OCT system.

8427-56, Session 11

Auto-correlation OCT

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OCT systems are, nowadays, established as a reliable tomographic tool, researchers are turning their attentions to develop new approaches on

new optical setups, signal processing and data analysis.

Bibliography data shows that Auto-correlation is usually treated as an unwanted feature in OCT images, and in this way researchers have proposed more than one way to avoid it. This study is focused in extract information and construct images based in the Auto-correlation interferometric signal.

The motivation is given mainly by the optical setup simplicity, reduced cost, sample movement insensibility. Is also interesting that, because is no need of reference arm, this optical configuration can be implemented in a single photonic chip. In other hand some features cannot be recovered, e.g., the first surface profile, and some morphological deformations, still this images could provide vital information about the sample.

An Auto-correlation OCT was implemented in Fourier domain, using an optical circulator, a SLED, a scanning system and a spectrometer as detector.

Tomographic image of a single histological slide was performed to validate the system, then more complex samples were tested. Beginning with plastic-air-plastic sandwich, the image showed all the structures with fidelity.

An multi layered adhesive tape (scotch tape roll) was also topographically reconstructed with good morphological agreement. Due to the sample birrefringence and set up properties polarization sensitive features could be seen and characterized.

Sample with more diffuse reflection were tested, aiming simulate some biological tissues. Images also could be performed, but with reduced depth.

The results so far has showed the system viability to be applied in biological samples, in this way the system are under improvements, mainly in optical coupling and alignment between optical elements to increase the signal/noise ratio. Different setups are also under implementation, such as swept-source, to study different aspects of each experimental possibility.

8427-57, Session 11

Coherence effects of thick objects imaging in interference microscopy

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Interference microscopy is an optical technique for objects surface profiling or visualization of objects volumetric structure. It combines high longitudinal resolution, peculiar to optical coherence tomography, with high lateral resolution, peculiar to optical microscopes. Interference microscopy in different modalities, such as full-field optical coherence tomography or confocal optical coherence microscopy, is used for volumetric visualization of biological tissues with cellular resolution.

Over the last decade a number of papers have been published on the theory of image formation in interference microscopes, which allowed better understanding of the coherence effects and optimization of parameters for image quality enhancement. However, most of these theories are created for a simple mirror in the sample arm and there is a lack of analysis of upper layers effect on imaging inner structures of the sample. Meanwhile, in a number of experimental investigations it was shown that utilizing both high numerical aperture and broad temporal spectrum produces peculiarities for imaging thick objects. To enhance image quality and achieve faster image acquisition, a better understanding of the physical effects arising in the interference microscope is necessary.

In this paper we propose a theoretical model of interference microscope image formation, which allows description on a unified basis of different interference microscope modalities, such as full-field OCT or confocal OCM. Using this model we analyze the coherence effects that arise in interference microscopes when imaging inner structure of a sample. The results of this analysis show, that the proposed theoretical model is suitable for interpretation of known experimental effects and can be used for optimizing interference microscopes parameters to enhance images quality and comprehensiveness.

8427-58, Session 12

Simultaneous EEG and diffuse optical imaging of seizure-related hemodynamic activity in the newborn infant brain

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An optical imaging system has been developed which uses measurements of diffusely reflected near-infrared light to produce maps of changes in blood flow and oxygenation occurring within the cerebral cortex. Optical sources and detectors are coupled to the head via an array of optical fibres, on a probe held in contact with the scalp, and data is collected at a rate of 10 Hz. A clinical electroencephalography (EEG) system has been integrated with the optical system to enable simultaneous observation of electrical and hemodynamic activity in the cortex of neurologically compromised newborn infants diagnosed with seizures. Studies have made a potentially critically important discovery of previously unknown transient hemodynamic events in infants treated with anticonvulsant medication. We observed repeated episodes of small increases in cortical oxyhemoglobin concentration followed by a profound decrease in 3 of 4 infants studied each with cerebral injury who presented with neonatal seizures. This was not accompanied by clinical or EEG seizure activity and was not present in nineteen matched controls. The underlying cause of these changes is currently unknown. We hypothesize that EEG gives an incomplete picture of the status of the brains of infants diagnosed with seizures. We also tentatively suggest that our results may be associated with a phenomenon known as cortical spreading depolarisation, not previously observed in the infant brain.

8427-59, Session 12

Optimization of wavelengths sets for multispectral reflectance imaging of rat olfactory bulb activation in vivo

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Wide field multispectral imaging of light backscattered by brain tissues provides maps of hemodynamics changes (total blood volume and oxygenation) following activation. This technique relies on the fit of the reflectance images obtain at two or more wavelengths using the modified Beer Lambert law [1]. It has been successfully applied to study the activation of several sensory cortices in the anesthetized rodent using visible light [2-3]. We have carried out recently the first multispectral imaging in the olfactory bulb [4]. However, the optimization of the wavelengths and wavelengths number has not been discussed in terms of cross talk and uniqueness of the estimated parameters (blood volume and saturation maps) although this point was shown to be crucial for similar studies in Diffuse Optical Imaging in humans [5]. We have studied theoretically and experimentally the optimal sets of wavelength for multispectral imaging of rodent brain activation in the visible using the approach proposed previously for Diffuse Optical Imaging . Sets of optimal wavelengths have been identified and validated in vivo for multispectral imaging of the olfactory bulb of rats following odor stimulus. We studied the influence of the wavelengths sets on the magnitude and time courses of the oxy and deoxyhemoglobin concentration variations as well as on the spatial extent of activated brain areas following stimulation. Beyond the estimation of hemodynamic parameters from multispectral reflectance data, we observed repeatedly and for all wavelengths a decrease of light reflectance. For wavelength longer than 590nm, these observations differ from those observed in the somatosensory and barrel cortex and question the basis of the

reflectance changes during activation in the olfactory bulb. To solve this issue, Monte Carlo simulations have been carried out to assess the relative contribution of absorption, scattering and anisotropy changes to the intrinsic optical imaging signals and will be presented.

1. M. Kohl, U. Lindauer, G. Royl, M. Kuhl, L. Gold, A. Villringer, et U. Dirnagl, "Physical model for the spectroscopic analysis of cortical intrinsic optical signals," Phys Med Biol 45, 3749-3764 (2000).

2. A. K. Dunn, A. Devor, A. M. Dale, et D. A. Boas, "Spatial extent of oxygen metabolism and hemodynamic changes during functional activation of the rat somatosensory cortex," Neuroimage 27, 279-90 (2005).

3. J. Berwick, D. Johnston, M. Jones, J. Martindale, P. Redgrave, N. McLoughlin, I. Schiessl, et J. E. W. Mayhew, "Neurovascular coupling investigated with two-dimensional optical imaging spectroscopy in rat whisker barrel cortex," Eur J Neurosci 22, 1655-66 (2005).

4. R. Renaud, H. Gurden, R. Chery, M. Bendhamane, C. Martin, et F. Pain, "Multispectral imaging of the olfactory bulb activation: influence of realistic differential pathlength correction factors on the derivation of oxygenation and total hemoglobin concentration maps," SPIE Proc vol 7902 (2011).

5. A. Corlu, T. Durduran, R. Choe, M. Schweiger, E. M. C. Hillman, S. R. Arridge, et A. G. Yodh, "Uniqueness and wavelength optimization in continuous-wave multispectral diffuse optical tomography," Opt. Lett. 28, 2339-2341 (2003).

8427-60, Session 12

Fluorescence-enhanced optical spectroscopy using early arriving photons in transmission mode: a finite element approach

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In the last decade, noninvasive near-infrared optical methods have been developed in order to detect tumors enclosed in biological media. Optical imaging of turbid media is a challenging problem mainly due to the scattering process that reduces image contrast and degrades spatial resolution. The development of fluorescent probes has recently improved the noninvasive optical technique. In this paper, we are interested in the time gating fluorescence signals. The diffusion approximation is used in order to describe the light propagation of a laser pulse in a turbid media that mimics breast like biological tissue. A numerical model based on a finite element method is proposed1. Fluorescence time dependent numerical simulations are performed in order to compute time-gated intensities resulting from line scans across partially absorbing and scattering slab configurations. Hidden objects are enclosed within this slab configuration that mimics a breast. Optical properties of objects are choosen to be the same as optical properties of breast tumor. In the presence of one hidden object in the slab, the results show the improvement of the lateral detection using the time-gating fluorescence technique in comparison to previous results obtained by means of the classical computation of photon propagation. Tacking into account two hidden objects, we investigate the lateral resolution aimed by fluorescence modality and we also compared the results to thus obtained by photon propagation. Similar trends were shown in a recent study devoted to detect fluorescent targets in small animals2. Different widths of the time gate are computed and it is demonstrated that both lateral localization of one inclusion, and resolution of two inclusions, are enhanced when the time-gate width (Dt) is decreased to about 50 ps. The overall computations confirm that fluorescent time-gating technique is very sensitive to local variations in optical properties that are due to breast like tumors in turbid media.

[1] J.-P. L'Huillier, V. Piron, and A. Humeau, "Detection of heterogeneities within turbid media by time-gated transillumination: study based on the finite element method," Proc. SPIE: European Conference on Biomedical Optics. 5862, 145-153, (2005).

[2] M. Niedre and V. Ntziachristos, "Comparison of fluorescence tomographic imaging in mice with early-arriving and quasi-continuous-wave photons," Opt Lett, 35(3), 369-371, (2010).

8427-61, Session 12

Optical projection tomography of the vascular network of living specimens

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Optical Projection Tomography (OPT) is a powerful three dimensional microscopy technique which is particularly suitable for studying millimeter-sized samples and organisms with typical resolutions of 2-10um.

Similarly to x-ray computed tomography, OPT is based on the acquisition of a sequence of optical transmission images through the sample at several angles. The acquired projections are mathematically combined to image the tissue in 3D.

Here we report a new contrast mechanism in OPT, given by the movement of cells present in bloodstream. Looking at a living transparent or weakly scattering sample it is possible to observe the flow of the blood cells. Therefore, by acquiring several time frames of the specimen and applying a motion-analysis algorithm, it is possible to obtain a map of the sample vasculature. We show that by mathematical processing the vascular maps obtained at different angles it is possible to produce and visualize a 3-D casting of the vasculature of the specimen, noninvasively and without the need for any fluorescent probe. This results in a low-cost, label-free, three-dimensional imaging technique able to visualize the vascular network of the living specimen.

In details, we describe our OPT system designed for in-vivo imaging of zebrafish (Danio-Rerio) at embryo and juvenile stage. The system is based on white light LED illumination and CMOS camera detection. Telecentric lenses are used to uniformly illuminate the sample and to select the light which primarily travels through the sample parallel to the optical axis of the camera. A stepper motor is used to rotate the sample over 360°.

We present the protocol for in- vivo imaging of the zebrafish. Firstly, the sample is anesthetized and mounted in a low melting point agarose gel. Then, it is included in a fluorinated ethylene propylene tube, which is immersed in water.

We describe the algorithms used for the motion detection analysis and for the 3D reconstruction of the virtual section of the specimen.

Finally we show in-vivo results showing the ability of the method to reconstruct the vascular network of the zebrafish and we validate the results with vibrotome sections.

8427-62, Session 12

Spectro-angular mapping of localized gold inclusions in Intralipid phantoms

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We have developed a new approach to map localized inclusions of gold nanoparticles in the Intralipid-1% liquid phantom. Our goal was to show that combined spectroscopic and angular snapshots of liquid phantoms and phantoms with inclusions allow obtaining information relevant for prostate cancer diagnostics and treatment. A combination of the point radiance spectroscopy and white light spectroscopy was used to measure angular resolved light distribution in 450-900 nm spectral range in Intralipid-1% liquid phantoms with and without localized inclusions of gold nanoparticles. Characteristic spectro-angular snapshots of the liquid phantom alone and with the localized inclusion of gold nanoparticles were obtained. For liquid phantoms without inclusions, the snapshots demonstrate wavelength dependent light distribution inside the turbid medium, visualize the transparency window and provide a quantification of angular spread of different wavelengths of light. For liquid phantoms with gold inclusions, the approach allows to isolate the spectroscopic signatures of the inclusions from the background, identify locations of the inclusions in the angular domain and quantify the detection limits in terms of the contrast value attainable for the selected quantity of gold nanoparticles located at the specific depth in tissue. A detection of 3x1013 particles up to 25 mm deep in Intralipid-1% was demonstrated. The encouraging results indicate a promising potential of radiance spectroscopy in prostate treatment and diagnostics with gold nanoparticles.

8427-63, Session 12

Photoacoustic spectroscopy of weakly absorbing media using nanosecond laser pulses

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Photoacoustic spectroscopy can be used to follow weak absorption changes in highly dispersive media such as the skin. A possible application is, for example, to map the distribution of photosensitizers used in the photodynamic therapy of skin lesions. Photoacoustic spectroscopy has enough sensitivity to detect very small amounts of compounds with characteristic absorption bands, or to detect compounds with very low absorption coefficients. In this work, we address the issue of the sensitivity of photoacoustic spectroscopy in the measurement the photoacoustic spectrum of pure water from 700 nm up to 2200 nm. The water absorption coefficients in this spectroscopic region range from 1E-3 up to 1E2 cm-1. The measurements were made using an OPO pumped by a Nd:YAG with 6 ns pulses and energies of a few µJ/cm2, and the detection employed a 2.25 MHz transducer. The photoacoustic spectrum of water thus obtained in is very good agreement with the known absorption spectrum of pure water. Parameters that can influence the sensitivity of the technique, such as the thickness of the sample probed, were evaluated. When the changes in absorbance are taken into consideration, the photoacoustic signal increases as the thickness of the region probed become smaller, that is, the signal decreases with the depth of the irradiated volume. The consequences of this dependence in the measurement of skin samples are tested and discussed.

8427-04, Poster Session

Line-scanning microscope with improved axial resolution

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In the last decade several techniques for light microscopy using structured illumination were developed in order to improve axial resolution. The general approach consists in the placement of a grid in the illumination path. Through its projection on the specimen the parts of the specimen from each focal plane are extracted. It normally demands for post processing that could make the method less attractive for some applications demanding very fast image acquisition. In any way the image acquisition time on these techniques is much smaller than in confocal microscopy. Theoretical analysis of the image formation as well as experimental results show that the axial resolution achieved in this type of microscope is comparable to that in confocal microscopes.

On the other hand since almost twenty years from several configurations of line-scanning microscopes have been reported. It consists on the use of slit or line illumination source and detector. The main goal was to improve the time consuming process of image acquisition in confocal microscopes. The line instead of a point detector obviates the need to make the scanning in one of the two lateral axes. It results in an anisotropic lateral resolution. Images of details perpendicular to the slit have a resolution similar to those obtained using a point detector. However the detector slit does not block out-of-focus light propagating along the slit direction so this lateral resolution is not improved in comparison to conventional microscopes.

The aim of this work is to improve the axial resolution of a line-scanning microscope through the implementation of computational techniques used for the extraction of a sectioned image from an array detector. This demands a different mathematical approach in order to eliminate the out-of-focus light. In fact light traveling transversally to the slit is blocked so these algorithms should be oriented to find light that arrive along the slit direction. It is also expected that the use of this out-of-focus subtraction techniques result in the elimination of anisotropy in lateral resolution.

Our experimental setup consists on a low-cost scanning-stage bench-microscope in brightfield reflection mode using a linear sensor. A stand-alone board for sensor readout purposes was developed as well as MATLAB applications to perform object positioning, sensor readout and image processing. Consequently this platform is suitable for developing and testing these algorithms. In order to assess image quality of this laboratorial prototype its contrast was measured. A scanning method for determination of Modulation Transfer Function (MTF) was used. Results of experimental MTF measurements from USAF target images had shown a cutoff frequency of 1095 lp/mm and a Strehl ratio of 0.96 with a 40x/0.65NA DIN Semi-Plan objective. The tests of these out-of-focus subtraction algorithms are being carried out using three-dimensional (3D) structures namely semiconductor devices and micromachined components.

8427-78, Poster Session

Laser scattering by transcranial rat brain illumination

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Due to the great number of applications of Low-Level-Laser-Therapy (LLLT) in Central Nervous System (CNS), the study of light penetration through skull and distribution in the brain becomes extremely important. The goal of this work is to determine the feasibility of LLLT on deep regions of CNS response of neural receptors due to continuous laser exposures. The aim is to analyze the possibility of precise illumination of deep regions of the rat brain, measure the penetration and distribution of red (λ = 660 nm) and Near Infrared (NIR) (λ = 808 nm) diode laser light and compare optical properties of brain structures. Both lasers were used in continuous wave mode, with 30 mW and a spot size of 1.8 mm. The rat (Rattus Novergicus) was anesthetized and sacrificed. In order to keep tissue optical properties the experiment was performed immediately after the sacrifice. The head of the animal was epilated and divided by a sagittal cut, 2.3 mm away from mid plane. This section of rat's head was illuminated with red and NIR lasers in points above three anatomical structures: cerebellum, hippocampus and frontal cortex (located: -6.0, -3.3, 2.5 mm from bregma). A coronal cut of the head was also made to allow the visualization of hippocampus by other direction. A high resolution camera (14,7 Mega pixels), positioned perpendicularly to the laser beam, was used to obtain images of the brain structures illuminated just with laser light. The images reveal that there are brain regions with different optical properties and light can be guided through white matter. Profiles of scattered intensities in the laser direction were obtained from the images. Tissue optical properties could be understood qualitatively with the study of these profiles. It is possible to estimate the intensity in hippocampus as 20% of the intensity in the skin (I) and the surface with intensity equal or higher than I/ is 25.0 mm2 deep. There is a peak in the scattered light profile corresponding to the skin layer. The bone layer gives rise to a valley in the profile indicating low scattering coefficient, or frontal scattering. It shows that craniotomy is not necessary to allow light access to deep regions at the brain. Another peak in the region related to the brain is an indication of high scattering coefficient for this tissue. There are few secondary peaks in the profile, which can be explained by reflections in brain's convolutions. Red and NIR light are well transmitted by skin and skull, but NIR light goes deeper in the brain. This work corroborates the use of transcranial LLLT in studies with rats which are subjected to models of CNS diseases. The outcomes of this study point to the possibility of transcranial LLLT in humans for a large number of diseases.

8427-79, Poster Session

Accurate determination of the complex refractive index of a solid tissue-equivalent phantom

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Tissue-equivalent phantom is becoming widespread as a substitute in the biological field to verify optical theories, test measuring systems and study the tissue performances for varying boundary conditions, sample size and shape at a quantitative level. Compared with phantoms made with Intralipid solution, ink and other liquid substances, phantom in solid state is stable over time, reproducible, easy to handle and has been testified to be a suitable optical simulator in the visible and near-infrared region. We present accurate determination of the complex refractive index (RI) of a solid tissue-equivalent phantom using extended differential total reflection method (EDTRM). Scattering phantoms in solid state were measured for p-polarized and s-polarized incident light respectively. The reflectance curves of the sample as a function of incident angle were recorded. The real part of RI is directly determined by differential of the reflectance curve, and the imaginary part is obtained from nonlinear fitting based on the Fresnel equation and Nelder-Mead simplex method. The EDTRM method is applicable for RI measurement of high scattering media such as biotissue, solid tissue-equivalent phantom and bulk material. The obtained RI information can be used in the study of tissue optics and biomedical field.

8427-80, Poster Session

Protein-based integrated optical sensor device

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The integrated optical Mach-Zehnder interferometer is a highly sensitive device, considered a powerful lab-on-a-chip tool for specific detection of various chemical and biochemical reactions. Despite its advantages, there is no commercially available biosensor based on this technique. The main reason is the inherent instability of the device due to slight changes of environmental parameters. In this paper we offer a solution to this problem that enables the optimal adjustment of the working point of the sensor prior to the measurement. The key feature is a control unit made of a thin film of the light-sensitive chromoprotein bacteriorhodopsin deposited on the reference arm of the interferometer. After showing the transfer characteristics of such a device, we demonstrate its applicability to sensing of specific protein-protein interactions. We expect our method to become a rapid and cost-efficient alternative of the commonly used measuring tools in protein research and medical diagnostics.

8427-81, Poster Session

Comparison between experimental and computational methods for scattering anisotropy coefficient determination in dental-resin composites

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Understanding the behaviour of light propagation in biological materials is essential for biomedical engineering and its applications. Among the key optical properties of biological media is the angular distribution of the scattered light, characterized by the average cosine of the scattering angle, called the scattering anisotropy coefficient (g). The value of g can be determined by experimentally irradiating the material with a laser beam and making angular-scattering measurements in a goniometer. In this work, an experimental technique was used to determine g by means of goniometric measurements of the laser light scattered off two different dental-resin composites. To assess the accuracy of the experimental method, a Mie theory-based computational model was used.

For laser irradiation, a randomly polarized He-Ne laser source was used (λ = 632.8 nm). The dental-resins composites studied presented two different types of inorganic filler (classified as nano and hybrid) with a similar organic matrix (polymeric). Independent measurements were used to determine some of the required input parameters for computation of the theoretical model, such as mean particle size and filler-volume fraction of the dental resins.

The values of g estimated with the computational method (nano-filled: 0.9399; hybrid: 0.8975) and the values calculated with the experimental method (nano-filled: 0.98297 ± 0.00021; hybrid: 0.95429 ± 0.00014) presented agreed well for both dental resins, with slightly higher experimental values. The higher experimental values (compared with Mie theory computations) may indicate that the scattering particle causes more narrow-angle scattering than does a perfect sphere of equal volume, assuming that with more spherical scattering particles the scattering anisotropy coefficient increases. Since g represents the angular distribution of the scattered light, values provided by both the experimental and the computational methods show a strongly forward-directed scattering in the dental resins studied, more pronounced in the nano-filled composite than in the hybrid composite.

8427-82, Poster Session

Measurements of scattering anisotropy in dental tissue and zirconia ceramic

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Knowledge of the optical properties of biological structures is useful for clinical applications, especially when dealing with incoming biomaterials engineered to improve the benefits for the patient. One ceramic material used currently in restorative dentistry is yttrium cation-doped tetragonal zirconia polycrystal (3Y-TZP) because of its good mechanical properties. However, its optical properties have not been thoroughly studied. Consequently, final restoration quality depends on detailed testing to ensure achieving the adequate material properties. Many methods for the determination of optical parameters from biological media are based on diffusion approximation, which makes the assumption that scattered light is isotropically distributed over all angles. However, real biological materials may have an angular dependence on light scattering, which may affect the optical behaviour of the materials. Therefore, the recovery of the degree of anisotropy in the scattering angular distribution is important. The phase function that represents the scattering angular distribution is usually characterized by the anisotropy coefficient g, which equals the average cosine of the scattering angle.

In this work, we measured angular-scattering distributions for two zirconia ceramic samples, pre-sintered and sintered, with similar thicknesses (0.48 mm and 0.50 mm, respectively). Measurements were also made for a dentine sample (0.41 mm in thickness). The samples were irradiated with a He-Ne laser beam (λ = 632.8 nm) and the angular-scattering distributions were measured using a rotating goniometer.

From the measurements, the g values yielded were: -0.7970 ± 0.0016 for pre-sintered zirconia, -0.2074 ± 0.0024 for sintered zirconia and 0.0620 ± 0.0010 for dentine. The corresponding average scattering angles were: 142.84° ± 0.15° for pre-sintered zirconia, 101.97° ± 0.14° for sintered zirconia and 86.45° ± 0.06° for dentine. The results show that the outcome of zirconia sintering process displays an optical behaviour more similar to those of dentine tissue, in terms of scattering anisotropy.

8427-85, Poster Session

Time of correlation of low-frequency fluctuations in the regional laser Doppler flow signal from human skin

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The laser Doppler flowmetry allows the non-invasive assessment of the skin perfusion in real-time, being an attractive technique to study the human microcirculation in clinical settings. Low-frequency oscillations in the laser Doppler blood flow signal from the skin have been related to the endothelial, neurogenic and myogenic mechanisms of microvascular flow control, in the range 0.0095-0.02 Hz, 0.02-0.06 Hz and 0.06-0.16 Hz respectively. The mean Amplitude (A) of the periodic fluctuations in the laser Doppler blood flow signal, in each frequency range, derived from the respective wavelet-transformed coefficients, has been used to assess the function and dysfunctions of each mechanism of flow control. Known sources of flow signal variances include spatial, temporal and inter-individual variability, diminishing the discriminatory capability of the technique. Here a new time domain method of analysis is proposed, based on the Time of Correlation (TC) of flow fluctuations between two adjacent sites. Registers of blood flow from two adjacent regions, for local temperature of 32 degrees Celsius (baseline) and thermally stimulated (42 degrees Celsius) of volar forearms from 20 healthy volunteers were collected and analyzed. The results obtained reveled high time of correlation between two adjacent regions when thermally stimulated, for signals in the endothelial, neurogenic and myogenic frequency ranges. Experimental data also indicate lower variability for TC when compared to A, suggesting a new promising parameter for assessment of the microvascular flow control.

8427-86, Poster Session

Load bearing studies of single DNA molecules and red blood cells using optical tweezers and Raman spectroscopy

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Raman scattering is a powerful tool for gaining information on the chemical structure of a studied sample. Previously, Raman scattering has been observed on single biomolecules.

The mechanics of biomolecules (such as DNA) continue to be studied extensively while questions remain pertaining to their chemical and structural response under strain. Conformational changes, under a controllable force, can be measured by combining Raman spectroscopy with optical trapping. We have applied this technique to measure the conformational changes in DNA and red blood cells (RBC).

The DNA molecule, a double-stranded lambda-DNA amplified at 12 kbp using standard polymerase chain reaction (PCR) techniques, is anchored at each end to optically trapped micron sized dielectric beads in aqueous solution. Owing to small width of DNA (2nm), Raman signal was amplified using Surface-Enhanced Raman Scattering (SERS). Utilizing the optical traps, DNA molecule is held in proximity to a silver coated bead (SERS agent). Raman peaks are excited with the help of a 532 nm beam. Under this configuration, a gradually increasing force is applied to the DNA while simultaneously recording the SERS spectra. With the increase in applied force on DNA, we were able to see a shift in the stretch mode of the phosphate backbone while there was no shift in the main vibrational peak of the cytosine base.

For RBC, two micron sized beads were trapped in a dual beam optical trap and was attached to opposite ends of an RBC obtained from a healthy donor. Moving one of the trap lead to the stretching of the cell. A 785nm beam, acting as Raman excitation, was incident at the edge of RBC. The cell was stretched and simultaneously Raman signal was acquired. We found that the proteins in the cell get maximally deformed when the cell is stretched while lipid signal remains practically unchanged. No enhancement technique was used in this case to amplify Raman signal.

8427-87, Poster Session

X-ray radiation-induced effects in human mammary epithelial cells investigated by Raman microspectroscopy

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Continued investigation on radiation interactions with cells and tissues is necessary to shed light into outstanding radiobiological issues such as the variation in patient radiosensitivity, the inability to monitor a patient's radioresponse during the course of an extended treatment, and the failure of current models to predict cell survival or tumour control at single high doses. Micro-Raman technique can be particularly useful in investigating the chemical changes induced in structure, protein, nucleic acid, lipid, and carbohydrate content of cells. Raman studies of cellular biomolecules have recently gained considerable attention, but there are only few works dealing with Raman investigation of cells exposed to X-ray. The aim of this work is to explore the possibility to employ micro-Raman spectroscopy in order to detect biochemical modifications in human mammary epithelial cells after exposure to graded X-ray doses. The differences observed in the peak of the aromatic amino acids, the amide I, amide III and nucleic acids may be indicative of damage in irradiated cells such as the fragmentation of individual amino acids and DNA bases, crosslink effects in molecular structure of DNA and protein conformational change unfolding because of the breakage of hydrogen bonds between peptide chains. Therefore our preliminary analysis indicates a good sensitivity of the micro-Raman technique to detect the chemical changes induced by X-radiation on fixed biological samples at subcellular level. Hence, this technique could be used in the field of radiation therapy to monitor the minimal doses sufficient to inactivate cancer cells thus reducing the overall radiation dose and minimising damage to the surrounding healthy cells. For this approach to be routinely adopted in clinical practice, it will be therefore crucial that future investigations provide a correlation between such structural and conformational changes and well-established radiobiological endpoints such as chromosomal damage and cell death.

8427-88, Poster Session

Monitoring of pathological changes in the skin

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The problem of fast non-invasive monitoring of the skin with detection of pathological changes and determination of their type requires an integrated approach which may be build on the basis of 3D visualization of the skin tissue (optical coherence tomography) and spectroscopic analysis of its layers. In current work a mathematical model of optical radiation interaction with skin tissues is build. This model takes into account as backscattered optical radiation as the effects of stimulated Raman scattering in visible and NIR spectra. The numerical simulations were carried out on the actual location of the pathological formations in skin layers using Monte-Carlo method. For each simulation the tissue topology was reconstructed on the optical coherent tomography imaging of the skin with different types of human skin formations. Specific peaks

are revealed in Raman scattering shifts for skin abnormalities irradiating by laser with wavelength 785 nm.

The possibility of significant increase in information content for optical coherence tomography and Raman spectroscopy joint usage is shown. It is achieved by significantly reducing of diagnostic measurements volume during the tissue layers allocation with OCT, followed by their analysis by Raman spectroscopy. Differences in Raman scattering intensities for abnormal and normal tissue layers are established, their values may differ by amount in 40% and higher with maximum nearby 1270, 1450 and 1650 cm-1.

8427-89, Poster Session

Investigation of cell morphology by the TRUImagE digital holographic microscopy system

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We report the development of the Three-dimensional Real-time Uninvasive Imaging and Evaluation (TRUImagE) system based on digital holographic microscopy to study the morphological changes in cells undergoing photodynamic therapy-induced cell death. The optical system, based on the Michelson interferometer and configured in transmission mode, and the sample holder incorporating a stage incubator have been developed for monitoring various tumorigenic cell samples without the use of markers. Off-axis digital holograms were recorded with a CCD sensor and numerically reconstructed to provide quantitative phase imaging and 3D morphology of the cells in real time. The system was used to continuously monitor and study, at different time points, the changes in cells after incubation with the photosensitizer followed by activation by the appropriate light dose. Results obtained from the TRUImagE system and biochemical assays will be given.

8427-90, Poster Session

3D CARS image reconstruction and pattern recognition on SHG images

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Nonlinear optical imaging techniques based e.g. on coherent anti-Stokes Raman scattering (CARS) or second-harmonic generation (SHG) show great potential for in-vivo investigations of tissue. [1,2] While the microspectroscopic imaging tools are established, automized data evaluation, i.e. image pattern recognition and automized image classification, of such nonlinear optical images bares great possibilities for future developments towards an objective clinical diagnosis.

This contribution details the capability of nonlinear microscopy for both 3D visualization of human tissues and automated discrimination between healthy and diseased patterns using ex-vivo human skin samples. By means of CARS image alignment we show how to obtain a 3D model of skin biopsy, which allows us to trace the tissue structure in different projections. Furthermore, the potential of nonlinear microscopy for diagnostic application by means of automated pattern recognition between healthy and keloidal skin tissue is discussed. The classification algorithm employs the intrinsic geometrical features of the collagen, which can be efficiently visualized by SHG microscopy. The shape of the collagen pattern allows conclusions about the physiological state of the skin, as the typical wavy collagen structure in healthy skin [3] is disturbed e.g. in keloid formation. Based on the different collagen patterns in healthy and diseased skin a quantitative score characterizing the collagen waviness - and hence reflecting the physiological state of the tissue - is obtained.[4]

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References

[1] C. Krafft et al., Analyst 134, 1046 (2009).

[2] N. Vogler et al., Laser Phys. Lett. 8, 617 (2011).

[3] P. Verhaegen et al., Wound Rep. Reg. 17, 649 (2009).

[4] A. Medyukhina et al., Biophotonics 4, 627 (2011).

8427-91, Poster Session

Mid infrared optical tweezers and nanosecond laser ablation on yeast and algae cells

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In recent years, lasers for optical trapping and micromanipulation of microscopic particles or cells and sub cellular structures, both in vivo and in vitro, have gained remarkable interest in biomedical research and applications. Ablation based on photochemical or photothermal processes requires efficient absorption of light by the biological molecules or by the water molecules. The absorption of ultraviolet light by biomolecules can lead to photochemical bond breakage, or heating. Although the principles and the mechanisms of pulsed laser ablation have been well described for macroscopic interventions, the microbeam operation under microscope guidance necessitates further investigation.

In this work, we present the research and development efforts towards a pulsed ultraviolet microbeam laser system (at λ=337 nm), the design and realization efforts towards an infrared laser trapping system (a cw Nd:YAG laser at λ=1064 nm) and the results obtained on yeast cells and algae by the combined system. The yeast cells have been invaluable experimental organisms due to their ease of genetic manipulation and dissection of molecular mechanisms while the small filamentous brown algae present on all coasts of temperate climate zones and it is one of the rare brown algae which is resistant to copper. We investigated the optical dissection of the cell versus the presence of optical trap forces and the presence of rhodamine dye, a well known photosensitizer. We observed that as the power of the laser optical trap increased the ablation threshold decreased. Although the wavelength of 1.06 μm is generally used for optical trapping, because biological samples are transparent for wavelengths near 1.0 μm, thus ensuring the lowest rate of absorption and minimize changes in the sample, one should be careful during the sample exposure to the laser trapping power, to avoid heating of the cell. We estimated the minimum energy of the microbeam for optical dissection of yeast cell under the influence of optical trapping forces as lower as 3 μJ, while in the presence of rhodamine as lower as 2 μJ, due to singlet oxygen production. Although the concentration of rhodamine did not affect the viability of cells, the combination with the microbeam reduced the ablation threshold. We characterized the laser ablation of the cell walls and resulting cavitation as plasma formation effects via a cascade ionization process, which create shock waves due to their occurrence only in nanosecond pulse mode irradiation. Lastly, using the techniques of optical microsurgery without influence of optical forces, we demonstrated the minimum energy value for sub cellular dissection on an algae cell equal to 27 μJ. It is important to note that the structure of algae within the sub cellular organelles exists; there is a cellular empty place into the cell, named “vacuole”. The existence of this empty place is favor to create shock waves which affect the ablation threshold. For pulse energy 27 μJ the pressure per unit mass is equal to 250 GPa/mass, this value is sufficient to introduce shock waves into cytoplasm.

8427-92, Poster Session

Diode laser based photoacoustic gas measuring instruments intended for medical research

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Analysis of breath and gases emanated from skin can be used for early and non-invasive diagnosis of various kinds of diseases. Two portable, compact, photoacoustic spectroscopy based trace gas sensors were developed for the detection of ammonia emanated from oral cavity and methane emanated from skin. Photoacoustic spectroscopy is a subclass of optical absorption spectroscopy and it measures optical absorption indirectly via the conversion of absorbed light energy into acoustic waves due to the thermal expansion of absorbing gas samples. The light sources were wavelength modulated, distributed feedback diode lasers emitting at the absorption lines of ammonia and methane, at 1.53 μm and 1.65 μm, respectively. Photoacoustic method ensures high selectivity, therefore cross-sensitivity was negligible even with large amount of water vapor and carbon dioxide in the gas sample. Various sampling tubes and chambers made of glass allowed direct sampling in order to prevent inaccuracies originating from adsorption-desorption processes and the application of sampling bags. In case of ammonia a preconcentration unit was used to achieve lower minimum detectable concentration. Gas sample from the oral cavity was pumped through a glass tube to the preconcentration unit that chemically bonded ammonia and released it when heated. By the alteration of gas sampling time ammonia concentration from 0.5 ppb to several ppm can be detected, furthermore without preconcentration unit even vol. % of ammonia can be measured. For oral cavity ammonia measurements the optimal gas sampling time was 15 s in order to achieve 10 ppb resolution and a dynamic range of 0-2000 ppb. For methane minimum detectable concentration of 0.25 ppm was found with 12 s integration time, and it was proved to be adequate for the detection of methane emanated from human skin and from mice. Moreover, the presented system can measure methane concentration over four orders of magnitude (0.25-2500 ppm). An ammonia and a methane sensor are currently installed at two medical research laboratories at University of Szeged and tested as instruments for non-invasive clinical trials. The aim of the measurements is to determine correlations between diseases or metabolic processes and emanated gases. Particularly correlation between halitosis (bad breath) and ammonia emanated from oral cavity is investigated. Besides, changes of methane concentration emanated from mouse (from breath and skin) related to different metabolic processes are examined. Preliminary results showed that gas concentration measurements are well reproducible and the devices can operate without adding chemicals. Consequently, instruments can be promising candidates for non-invasive diagnostic tests.

8427-93, Poster Session

Dual wavelength multiple-angle light scattering system for cryptosporidium detection

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A simple, dual wavelength, multiple-angle, light scattering system has been developed for detecting cryptosporidium suspended in water. Cryptosporidium is a coccidial protozoan parasite and the causative agent of cryptosporidiosis; a diarrhoeal disease of varying severity. The parasite is transmitted by ingestion of contaminated water, particularly drinking-water, but also accidental ingestion of bathing-water, including swimming pools. It is therefore important to be able to detect these parasites quickly, so that remedial action can be taken to reduce the risk of infection. The proposed system combines multiple-angle scattering detection of two wavelengths, to collect relative wavelength angle-resolved scattering phase functions from the cryptosporidium oocytes in suspension, and multivariate data analysis techniques to obtain characterizing information of samples under investigation. The system was designed to be simple, portable and inexpensive. It employs two diode lasers (violet InGaN-based and red AlGaInP-based) as light sources and silicon photodiodes as detectors and optical components, all of which are readily available. The measured scattering patterns showed that the relative wavelength angle-resolved scattering pattern of cryptosporidium oocytes were significantly different from other particles (e.g. polystyrene latex sphere, milk). The system performance was initially validated by differential measurement of the concentrations of both cryptosporidium oocytes suspended in de-ionised water and mixtures of cryptosporidium oocytes and polystyrenes latex beads of different sizes in aqueous suspension. The measurement results showed good agreements with the control reference values. These results indicate that the proposed method could possibly be applied to online detection of the water quality control system.

8427-94, Poster Session

Real-time processing of laser speckle imaging for fast blood flow visualization

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The real-time video frame rate visualization of blood flow using laser speckle imaging (LSI) is quite important in clinical diagnosis and in basic researches of life science. However, it is difficult to achieve a real-time visualized LSI due to the heavy computation burden on the personal computer platform. In this paper, several methods are introduced to accomplish a real-time visualized LSI system. These methods are using various hardware and corresponding algorithms to improve the processing performance of laser speckle imaging data, including by using graphics processing unit (GPU), digital signal processor (DSP) and dedicated circuit in field programmable gate array (FPGA).

The optimization of the bandwidth becomes an attractive solution to improve the performance. As the bandwidth increases, the more data elements can be fetched at one memory operation. In this situation, more processing units can be added to handle the extra data elements to improve the overall performance. The GPU is of such an architecture owning big bandwidth and rich processing units. So it is quite appropriate for the handling of the compute-intensive and data-intensive tasks by employing the massive parallel processing, such as laser speckle imaging analyzing. Based on the GPU method, a 12-60 fold performance enhancement is obtained in comparison to the optimized CPU implementations in our experiments.

The size and power dissipation is a little larger for the GPU based LSI method, as the GPU must be installed on a PC (personal computer). To accomplish a portable LSI instrument with small size and power dissipation, DSP is used by us to perform the processing of LSI due to the powerful real-time processing capabilities and power efficiency. In vivo experiments demonstrate that this portable LSI system can obtain blood flow images at 25 frames per second with the resolution of 640 × 480 pixels.

To further improve the processing capability of this kind of portable LSI system, a novel hardware-friendly algorithm for the real-time processing of laser speckle imaging is developed by us. Based on this algorithm, a dedicated hardware processor for real-time processing of laser speckle imaging data in the field programmable gate array (FPGA) is designed. The pipeline processing scheme and parallel hardware architecture are introduced into the design of this type of LSI hardware processor in order to further improve the processing performance. When the LSI hardware processor is implemented in a low-cost FPGA running at the maximum frequency of 130 MHz, up to 85 raw images with the resolution of 640×480 pixels can be processed per second. Compared with the GPU solution and DSP solution, this hardware-based LSI processor can achieve real-time processing at very low clock frequency and power dissipation but with high performance. Besides, we also present a system on chip (SOC) solution for LSI processing by integrating the CCD controller, memory controller, LSI hardware processor, and LCD display controller into a single FPGA chip. This SOC solution also can be used to

produce an application specific integrated circuit for LSI processing.

Finally, the comparison of these several methods for real-time visualized LSI are also presented in terms of easiness of system integration, processing speed, portability and some trade-offs.

8427-95, Poster Session

Laser based signal and image fractal analysis for assessment of blood flow

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Laser based techniques offer non invasive means of imaging and optical signal acquisition in the biomedical field. Laser Doppler flowmetry and laser speckle imaging are important laser based methods in current research and have been explored for the analysis of blood flow. Doppler flow meters as well as laser speckle imagers use tissue backscattered light to non-invasively assess the blood flow rate. While because of large spatial variability and the temporal heterogeneity in tissue microvasculature, the measured blood flow rate is expressed in relative units in laser Doppler, laser speckle methods offers a whole field imaging resulting in absolute measurements of flow velocity. Measurement and analysis of blood flow is vital in evaluating normal as well as differently diseased conditions of the human body. Several parameters related to flow along with flow velocity are important in characterizing tissues based on blood flow. Complexity of the flow is one of such important parameters which could be explored for analyzing different conditions of the body. The complexity of the signal / image obtained from target region of the body could reflect the corresponding complexities related to the flow. The fractal nature exhibited by these signals / images could be useful as a tool for obtaining important pieces of information regarding their complexity and in turn of the flow. Laser Doppler signals and laser speckle images have unique fractal properties from the reported literature. Thus estimating the fractal dimensions and associated parameters of these signals would give valuable information regarding the nature of the flow. In this paper, we are analysing the results of blood flow complexities assessed through fractal dimensions of Doppler signals and speckle images acquired from different parts of the body. A comparison of different methods of fractal dimension analysis and calculation has been carried out for both laser Doppler signals and laser speckle images. The method adopted is expected to serve as a helping tool in characterizing normal and malignant tissues with associated variation in blood flow complexities based on the values of obtained fractal dimensions associated parameters in such cases.

8427-96, Poster Session

Water-soluble conjugated polyelectrolytes for highly sensitive and selective potassium ion detection

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Conjugated polyelectrolytes (CPEs) have established themselves as a platform in chemical- and biological sensors with high sensitivity by virtue of their light harvesting properties. Extensive studies have been performed to develop CPE-based fluorescent assays for the detection of DNA, RNA, peptides, etc with signal amplification utilizing a fluorescence resonance energy transfer (FRET) mechanism.

Recently, Plaxco et al. reported that cationic CPEs can open the stem-loop structure of molecular beacons (MBs) through both electrostatic and hydrophobic interactions between the CPEs and MBs. These exciting results prompted us to investigate a new homogeneous sensing scheme utilizing the interactions of a molecular beacon aptamer (MBA) and CPEs. MBAs are MB-based oligonucleotide probes with a target-specific aptamer sequence in the loop part. Combining the binding specificity of a G-quadruplex forming MBA and signal transduction via the complexation of MBA and CPEs may provide an opportunity to design and develop selective and sensitive fluorescent assays for a target species.

Here we demonstrate highly sensitive and selective potassium detection against excess sodium ions, by modulating the interaction between the G-quadruplex-forming MBA and cationic CPEs. The hairpin-type MBA labeled with a fluorophore (6-carboxyfluorescein, 6-FAM) and quencher (4-(4'-dimethylaminophenylazo)benzoic acid, DABCYL) at both 5'- and 3'-termini underwent a conformational change (by complexation with CPEs) to either an open-chain form or a G-quadruplex in the absence or presence of K+ ions. This selective event induces the amplified PL signal from the fluorophore via fluorescence resonance energy transfer (FRET) from CPEs without K+ (on-state), whereas the almost complete quenching of fluorophore emission was observed with K+ (off-state). The potassium ion-specific G-rich base sequence in the MBA provides the selectivity against a range of metal ions and optical amplification via FRET from CPEs gives remarkable detection sensitivity. A detection limit of ~1.5 nM was achieved, which is ~3 orders of magnitude lower than those previously reported. The successful detection of 5'-adenosine triphosphate (ATP) with the MBA containing an ATP-specific aptamer sequence was also demonstrated using the same sensor scheme. The scheme reported herein can be extended further to sensing other types of G-rich aptamer-binding chemicals and biomolecules. A combination of a high binding specificity of biosystems and synthetic CPEs with tunable optical amplification properties provided the ultimate detection sensitivity and selectivity.

8427-97, Poster Session

Spectroscopic detection of chemotherapeutics and antioxidants

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The hand-foot-syndrome presents a severe dermal side-effect of chemotherapeutic cancer treatment. A possible cause for this side-effect is the leakage of systemically administered chemotherapeutics with the sweat. Transported to the skin surface via glands the drugs subsequently penetrate into the skin like topically applied substances. Once accumulated in the skin the chemotherapeutics destroy cells and tissue - in the same way as they are supposed to act in destroying cancer cells.

Aiming at the development of strategies to elucidate the molecular mechanism underlying the hand-foot-syndrome (and, in a second step, strategies to prevent this severe side-effect), it is important to evaluate the concentration and distribution of chemotherapeutics and antioxidants in the human skin. The latter can be estimated by the carotenoid concentration, as carotenoids serve as marker substances for the dermal antioxidative status [1].

Following the objectives outlined above, this contribution presents a spectroscopic study aiming at the detection and quantification of carotenoids and selected chemotherapeutics in human skin. To this end spontaneous Raman scattering [2] and coherent anti-Stokes Raman scattering (CARS) microspectroscopy are combined with two-photon excited fluorescence. While the latter technique is restricted to the detection of fluorescent chemotherapeutics, e.g., doxorubicin, the vibrational spectroscopic techniques can - in principle - be applied to all analyte molecules. The results of quantitative spectroscopic studies are as well discussed as penetration studies of chemotherapeutics in mammalian skin. Furthermore, we will present a novel and very flexible ps-laser based setup for epi- and forward CARS microscopy utilizing a fiber-optic switch and a spectrometer for signal detection.

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[1] Maxim E. Darvin et al., J. Biomed. Opt. 13, 044028 (2008); doi:10.1117/1.2952076

[2] Werncke et al., Laser Phys. Lett., 1-6 (2011) / DOI 10.1002/lapl.201110081 1

8427-98, Poster Session

Laser heating of gold nanoparticles: photothermal cancer cell therapy

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In this work an application of gold nanoparticles in in-vitro photothermal cancer cell therapy is demonstrated. Gold nanoparticles with different diameters ranging between 40 and 200 nm are mixed with HeLa cancer cells. After incubation, the nanoparticles are found to be deposited on the cells membrane or enter into the cell. Pulsed laser radiation delivered by Nd:YAG system is used to irradiate the samples. The cell viability as a function of the irradiation time, wavelength of the incident irradiation, particle dimensions, and laser fluence is estimated. The nanoparticles heating and cooling dynamics is traced by a numerical model based on heat diffusion equation combined with generalized Multiparticle Mie theory for calculation of the optical properties of nanoparticles. Optimal conditions ensuring high efficiency of cancer cell killing are defined.

8427-99, Poster Session

Multifunctional nanoparticles for imaging applications

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The development of highly specific markers for fluorescent microscopy has become a very popular research topic. Organic fluorophores have several drawbacks, such as photo bleaching and autofluorescence. Therefore increasing interest in inorganic quantum dots or nanoparticles has been observed because of their unseen photo-stability and cost-effective synthesis. When these nanoparticles are coated with proteins, they could serve as specific markers in fluorescent microscopy experiments. Coating the surface of the nanoparticles with trialkoxysilanes introduced functional groups for subsequent covalent coupling to proteins. In this case iron oxide nanoparticles were compared to the same particle with an extra gold shell. The plasmonic properties of this shell could greatly enhance the contrast in microscopy applications. The selected targets for these experiments were microorganisms. By using an optical darkfield microscope, the nanoparticles were visualized inside thin polymer films and microorganisms. The darkfield mode of the microscope allows detection of nanoparticles, which normally would be under the diffraction limit and thus be undetectable. This approach could have great potential as a labeling technique, since it combines the non-photobleaching, photo-stable nanoparticles with the possibility to introduce highly selective proteins onto the surface.

8427-100, Poster Session

Multispot two-photon imaging of mice heart tissue detecting calcium waves

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High rate, full field image acquisition in multiphoton imaging is achievable by parallelisation of the excitation and of the detection paths. Via a Diffractive Optical Elements (DOEs) which splits a pulsed laser, and a spatial resolved descanned detection path, a new approach to microscopy has been developed. By exploiting the three operating mode, single beam, 16 beamlets or 64 beamlets, the best experimental conditions can be found by adapting the power per beamlet. This Multiphoton Multispot system (MCube) has been characterized in thick tissue samples, and subsequently used for the first time for Ca2+ imaging of acute heart slices. A test sample with fixed mice heart slices with embedded sub-resolution fluorescent beads has been used to test the capability of optical axial resolution up to ~200 microns in depth. Radial and axial resolutions of 1.2 microns and 3 microns have been respectively obtained with a 20X water immersion objective, getting close to the theoretical limit. Then images of heart slices cardiomyocites, loaded with Fluo4-AM have been acquired. The formation of Ca2+ waves during electrostimulated beating has been observed, and the possibility of easily acquire full frame images at 16Hz (16 beamlets) has been demonstrated, towards the in vivo study of time resolved cellular dynamics and arrhythmia trigger mechanisms in particular.
A very high speed two-photon Random Access system for in vivo electrophysiological studies, towards the correlation of voltage and calcium signals in arrhythmia phenomena, is now under developing at Light4Tech. The research leading to these results has received funding from the European Community's Seventh Framework Program FP7/2007-2013 under grant agreement no HEALTH-F2-2009-241526, EUTrigTreat.

8427-102, Poster Session

Quenching of nanomarkers phosphorescence by heavy metals ions and energy acceptors in determination of structural changes in proteins

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For investigation and diagnosis of nanosystems such as proteins we use heavy atom effect and triplet-triplet (T-T) transfer of electronic excitation energy. Choice of these processes is caused by the fact, that they both are realized in encounter complex of nanomarker and quencher. Complex formation is defined by protein state in aqueous solution. For realization of heavy atom effect we used complexes consisting of nanomarker and heavy metal ion, and for energy transfer - coplexes, consisting of energy donor and acceptor.

Investigation of heavy atom effect was carried out by fluorescence and phosphorescence quenching and by decrease in lifetime of nanomarkers. Dyes from xanthene row (eosin, erythrosin, rose bengal) and acridine row (trypaflavine and acridine orange) were chosen as polar nanomarkers. As nonpolar nanomarkers we choose polycyclic aromatic hydrocarbons - anthracene, pyrene and other. Ions of thallium, iodine and lead served as quenchers of electronic excited states of nanomarkers. Study of quenching processes was carried out in buffer solutions of human serum albumin and bovine serum albumin. For studying of T-T energy transfer we chose eosin as energy donor and anthracene as energy acceptor both non-covalent bonded to proteins.

It is established that nanomarkers phosphorescence quenching by heavy metals and energy acceptors takes place in protein microphase. It is shown that Stern-Folmer constant of phosphorescence quenching by heavy metals and rate constant of T-T energy transfer are sensitive to structural changes in proteins. Dependence of eosin phosphorescence intensity on sodium dodecylsulfate concentration allows to establish two-stage nature of the proteins structure changes under surfactants action.

It follows from obtained data, that rate constants of triplet states quenching don't correlate with constant of spin-orbital interaction which is proportional to fourth power of nucleus charge of chosen heavy atoms. Possibly, it is connected with more complex mechanism of heavy metals salts interaction with proteins, than simple coulomb interactions.

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8427-105, Poster Session

Optical tractor beam for novel micromanipulations of target cells

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We present a fundamentally distinguished schematic for a novel micromanipulation which realizes stable trapping and continuous optical traction/pulling of molecules at one go, opening up its widely appealing potentials in physics and biomedical engineering. We will for the first time theoretically investigate the origin of pulling force by modeling tractor beams and its explicit correlations on the laser types, particle's parameters, and beam polarization modulation. The novel technology of tractor beam is developed and proposed via a systematic analysis from electromagnetic scattering theory, condition of pulling force, and experimental investigation by using binary-lens optics. The binary optics technique can effectively bend the wave-vector and (or) polarization of the light, which is exploited in the design of the binary grating lens to generate a well-collimated Bessel beam after the focusing lens. The laser's k-vector is bent such that large cone angle can be formed so as to produce the tractor beam.

Our technique is an exact counterpart of optical tweezer: realization of a backward scattering force by a light beam without creating an equilibrium point of gradient (i.e., optical tweezer). In order for normal optical tweezer to achieve a large optical gradient force for trapping, it is necessary to use high numerical aperture microscope objectives that will limit the working distance, but our new method based on tractor beam can greatly overcome this bottleneck. The major criterion is to manipulate the beam-particle interference to maximize the transfer of momentum along the forward direction, so that the reaction force will be dragging the particle all the way towards light source continuously, i.e., the fantasy of tractor beam. We will tailor the setup and demonstrate its unique applications in cell sorting and stretching, which may be helpful in separating pre-targeted cells and diagnosing infected cells (e.g., Malaria infected cells). We can get rid of the confinement imposed by the limited size of high NA microscope, and can manipulate the force to be pulling, pushing, trapping, and any combination of the aforementioned.

8427-107, Poster Session

The parameters of oxidative stress in cervical cancer tumors under femtosecond laser irradiation

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The present work will describe the influence of the femtosecond laser irradiation on neoplasm in vivo in white mice with transplantable cervical cancer tumor (cervical carcinoma-5, with the tumor strain provided by Blokhin Russian Cancer Research Center). Erbium femtosecond fiber laser, a joint development of Fiber Optics Research Center of the Russian Academy of Science and Ulyanovsk State University, was employed for the experiments. The parameters of all-fiber erbium laser were the following: the pulse duration is 10-13s, the average lasing power is 1,3 mW; the peak power of the generated pulses is 6 kW, and the operating wavelength is 1.55μm.

To estimate the oxidative stress properties the following parameters were measured in neoplasm: malondialdehyde level, activity of superoxide dismutase, catalase, glutathione reductase, and glutathione- S'-transferase.

The statistical processing of the obtained was performed using U-Mann-Whitney test (Stata v.6.0).As follows from the experiments, on the 20 th day of tumor growth, the femtosecond laser irradiation increases the malondialdehyde level in neoplasm depending on the doze. Changes in the antioxidant enzyme activity were determined to be dependent on femtosecond laser radiation dose and the stage of experimental tumors. The data obtained allow suggesting appearance of strong oxidative stress in cervical cancer tumor -5 under the femtosecon laser irradiation.

8427-108, Poster Session

Improvement of axial resolution of spectral domain optical coherence tomography with wide band PLC splitter

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We report the development and performance of high resolution spectral domain optical coherence tomography (SD-OCT) system based on 2×2 planar lightwave circuit (PLC) splitter that was designed as a single mode splitter at near infrared and used as the beam splitter for a SD-OCT system. The splitter has been made by coupling SMFs to a planar lightwave circuit (PLC) splitter chip. The PLC splitter chip was fabricated to have a single mode property with 750 nm cutoff wavelength and the SMFs, which have 730 nm cutoff wavelength, were securely connected to the PLC chip through fiber block arrays having lithographically fabricated V grooves. With the implemented PLC splitter, we have obtained a low excess loss of 0.4 ~ 0.7 dB over a wide wavelength range from 730 nm to 950 nm. With the proposed 2×2 PLC splitter and homemade WDM coupler(840 nm/880 nm) by using fused biconical tapered (FBT) method, SD-OCT images of samples successfully obtained by using combined source with 840 nm and 880 nm SLDs.

8427-109, Poster Session

Effect of probe angle for diffuse reflectance spectroscopy on human skin

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Diffuse reflectance spectroscopy is a popular optical measurement technique for noninvasive optical diagnostics. Specifically, diffuse reflectance spectroscopy is in research for detect tissue optical properties of human skin and for optical imaging based on the measured optical intensity distributions.

When the spectroscopic measurement is performed with a fiber optic probe, it provides a quantitative characterization of skin tissue optical properties. During spectroscopic reflectance measurements with a fiber optic probe, the pressure on a human skin and angular configuration of fiber optic probe will affect the skin tissue optical properties.

The purpose of this study is to investigate the effect of probe angular configuration on spectroscopic measurements of human skin, and thereby to obtain the quantitative relationship between the reflectance characteristics and probe angles. Meanwhile, effects of angular displacements are investigated since angular displacement of human body, for example, arms, is a usual perturbation due to movement during a measurement. The experimental setup is composed of a light source with deuterium tungsten halogen lamp, a spectrometer for visible and near infrared wavelengths, and a fiber optic probe for reflectance spectra sampling. For measuring the reflectance spectra with variable angles, a variable angle fiber holder is used.

The wavelength dependence on angular configuration is analyzed for visible and near infrared ranges. We analyze the effect of time-dependent angular perturbation on human skin measurement. From the investigations, the effect of probe angles on reflectance spectra, angular tolerance and reliability of measurement are estimated.

8427-110, Poster Session

Photoacoustic tomography: ultrasonically breaking through the optical diffusion limit

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We develop photoacoustic imaging technologies for in vivo early-cancer detection and functional or molecular imaging by physically combining non-ionizing electromagnetic and ultrasonic waves. Unlike ionizing x-ray radiation, non-ionizing electromagnetic waves-such as optical and radio waves-pose no health hazard and reveal new contrast mechanisms. Unfortunately, electromagnetic waves in the non-ionizing spectral region do not penetrate biological tissue in straight paths as x-rays do. Consequently, high-resolution tomography based on non-ionizing electromagnetic waves alone-such as confocal microscopy, two-photon microscopy, and optical coherence tomography-is limited to superficial imaging within approximately one optical transport mean free path (~1 mm in the skin) of the surface of scattering biological tissue. Ultrasonic imaging, on the contrary, provides good image resolution but has strong speckle artifacts as well as poor contrast in early-stage tumors. Ultrasound-mediated imaging modalities that combine electromagnetic and ultrasonic waves can synergistically overcome the above limitations. The hybrid modalities provide relatively deep penetration at high ultrasonic resolution and yield speckle-free images with high electromagnetic contrast.

In photoacoustic computed tomography, a pulsed broad laser beam illuminates the biological tissue to generate a small but rapid temperature rise, which leads to emission of ultrasonic waves due to thermoelastic expansion. The short-wavelength pulsed ultrasonic waves are then detected by unfocused ultrasonic transducers. High-resolution tomographic images of optical contrast are then formed through image reconstruction. Endogenous optical contrast can be used to quantify the concentration of total hemoglobin, the oxygen saturation of hemoglobin, and the concentration of melanin. Melanoma and other tumors have been imaged in vivo. Exogenous optical contrast can be used to provide molecular imaging and reporter gene imaging.

In photoacoustic microscopy, a pulsed laser beam is focused into the biological tissue to generate ultrasonic waves, which are then detected with a focused ultrasonic transducer to form a depth resolved 1D image. Raster scanning yields 3D high-resolution tomographic images. Super-depths beyond the optical diffusion limit have been reached with high spatial resolution.

Thermoacoustic tomography is similar to photoacoustic tomography except that low-energy microwave pulses, instead of laser pulses, are used. Although long-wavelength microwaves diffract rapidly, the short-wavelength microwave-induced ultrasonic waves provide high spatial resolution, which breaks through the microwave diffraction limit. Microwave contrast measures the concentrations of water and ions.

The annual conference on this topic has been doubling in size approximately every three years since 2003 and has become the largest in SPIE's Photonics West as of 2009.

8427-111, Poster Session

The study of sensitivity of boundary integral method to detect of depth of tumor

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The target of this paper is the evaluation of boundary integral method (BIM) for image reconstruction. To do it, the propagation of photon in biological phantom like breast tissue is studied by BIM. The diffuse equation is widely used to study of propagation of photons in the biological tissues. This equation is solved by numerical methods such as BIM and FEM. To study of photon migration in turbid media, several phantoms with optical properties like breast tissue in NIR are prepared. These phantoms are inhomogeneous and known tumors in different depth are located in these phantom. The phantom is illuminated by laser (@780 nm) and the transmitted photons are transferred by optical fibers to detectors. Then the surface intensity of laser is applied to detect of tumor depth. To detect of tumor, the codes based on BIM and FEM are used. The results obtained by BIM and FEM are compared and the accuracy of BIM is evaluated. Also, for different value of depth of tumors, the sensitivity of BIM is studied. The purpose of this research study is the evaluation of BIM for image reconstruction. Our previous publications show the computational time of BIM is lower than FEM; but in this paper, the precision of this code for depth detection can be studied. The depth of different tumor are measured by BIM and compare with actual depth, so the sensitivity and signal to noise ratio of used experimental setup is studied.

8427-112, Poster Session

Theoretical analysis of two nodal-wedges method to enhance the vibration behavior of NSOM probe with its tip being immersed partially in liquid

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Theoretical analysis of two nodal-wedges method to enhance the vibration behavior of NSOM probe with its tip being immersed partially in liquid

In this study, the tuning fork-fiber probe system for near-field scanning optical microscope (NSOM probe), whose fiber tip is immersed partially in liquid and vibration behavior is controlled mechanically with two nodal-wedges method, is modeled by bending vibration equations. And also its resonant characteristics are numerically investigated by solving the system of equations. For the two nodal-wedges method, pin point and knife-edge point are newly introduced into a typical NSOM probe, and the resonant characteristics are enhanced by adjusting properly their contact positions to the axis of the fiber probe.

The NSOM probe with two nodal wedges is regarded as a coupled system of 6 vibration beams which are bounded by the pin point, the knife-edge point, the glued point of the fiber probe and the tuning fork, the liquid surface, and end points of two prongs. The effect of fiber tip's immersion into liquid is considered by the liquid resistance to probe motion and the flow of the liquid in the vicinity of the probe. In order to solve the system of equations, expressions with damping terms and 24 undetermined coefficients are introduced for the general solutions of six vibration beams, and 24 boundary conditions are applied for 7 boundary points.

From the numerical analysis, it was confirmed that the resonant characteristics of the NSOM probe with its tip being immersed partially in liquid could be enhanced by adjusting the contact positions of pin and knife edge points as in air. The resonant frequency and the Q value of the NSOM probe were changed periodically by shifting the contact position of the knife-edge point along the fiber probe, and were gradually decreased by increasing the immersion depth of the fiber tip. Finally, the optimal control condition for two nodal-wedges method was found.

8427-113, Poster Session

Comparison of laser-assisted damage in porcine liver using multi-directional and foward firing fiber

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Laser-assisted endoscopic surgery is made possible by employing optical waveguides such as fiber optics and hollow wave-guides. In some applications of laser-assisted endoscopic surgery, it is necessary to change the direction of the light emission. Our group reported a new fabrication method for multi-directional firing fibers. The conical surface of the fiber tip made the multi-directional emission of the laser light at the distal end of the fiber. In this study, we employed the multi-directional firing fiber for the laser-assisted coagulation of the soft tissue. The developed fiber and the normal forward-firing fiber are used for the endoscopic delivery system of the continuous IR laser into the in vitro porcine liver. The ablation and coagulation pattern were compared for two distinctive fiber systems. Regardless of the laser's parameters, the

multi-directional firing fiber produced a cavity and coagulation zone with more or less a circular shape, while the forward fiber produced an elongated cavity and coagulation region. The multi-directional firing fiber produced wider and shorter coagulation and cavity zones compared to that of the forward-firing fiber. We expect the multi-directional firing fiber to be an excellent optical delivery system for the endoscopic laser-hyperthermia for various tumors in liver, breast and thyroid.

8427-114, Poster Session

Optical biosensors utilizing polymer-based athermal microring resonators

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Optical waveguide biosensors are attracting more and more attentions and presenting great potential applications. Polymer-based optical biosensors are promising for the their unique advantages: low cost, easy fabrication, possibility of functionalization with chemicals for the detection of biological molecules, and flexible operating wavelength in both the infrared communication wavelength band (1310-1550nm) and the visible wavelength region (500-800nm). Operating in the visible wavelength, the optical biosensing can avoid the high optical absorption loss of water solution, which can hardly be done for Si-based optical sensors.

In this paper, an optical biosensor utilizing polymer-based athermal optical waveguide microring resonator is presented. The athermal design of the microring resonator can make the resonant wavelength drift with temperature be greatly reduced, and an optical biosensing platform with high thermal stability can be achieved. The simulation results show that the maximal resonant wavelength drift is -0.0085nm when the temperature varies from 20° to 65° and the maximal wavelength drift slope is -0.0009nm/K . With the microring resonators fabricated by using a simple UV based soft imprint technique with self-developed UV-curable polymer PSQ-L materials, experimental investigations on the bulk refractive index (saline solution) and specific surface detection of target molecules (avidin molecules) have been preliminarily performed. The results shows that the optical biosensors based on the polymer optical microring resonators would have potential applications for bulk sensing, label-free surface sensing, and also for detection of labelled molecules with coloured tags.

8427-115, Poster Session

Analysis of skin basalioma and melanoma by multispectral imaging

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Multispectral optical density (OD) images of skin basaliomas and melanomas in the spectral region 450 - 950 nm with step 10 nm were taken and analysed. We compared parametric maps of the melanin index M = 100 (OD650 - OD700), erythema index E = 100 (OD560 - OD650) and specific parameter p = OD650 + OD950 - OD540 to find method that would help oncologists to decide about the excised area of skin cancers. So far 5 histologically confirmed basaliomas and 19 histologically confirmed melanomas were investigated. The first results show that melanomas have higher melanin index than basaliomas, the erythema index varies from negative to positive values in different melanoma areas while basaliomas have only positive erythema indices. The p maps for melanomas show areas where p values are higher than healthy skin around the pathology, while basaliomas have lower p values than the surrounding skin.

8427-116, Poster Session

Three-dimensional scaffolds for bone tissue engineering

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Direct fs laser writing (DLW) by multiphoton polymerization (MPP) is a technique which allows the fabrication of three-dimensional (3D) structures, with sub-100 nanometer resolution. DLW has found applications in photonics, microoptics, microfluidics, as well as in biomedicine. One of the most promising biomedical applications of DLW is engineering of artificial tailor-made tissues, which could be transplanted into patients to cure diseases or traumas. DLW has been employed for the fabrication of artificial scaffolds, which could serve as an extra-cellular matrix (ECM) and sustain stem cell growth in vitro. The topography of the scaffolds can affect cell viability, adhesion and direct their differentiation. This can be used for constructing artificial tissues of desirable form and functionality.

In this work we present the latest results on DLW application in tissue engineering, by fabricating micro-structured artificial 3D scaffolds and investigating their interaction with pre-osteoblastic cells. Nonlinear absorption cross-sections of photoinitiators used were measured with Z-scan technique. Z-Scan is a particularly sensitive and easy technique to measure nonlinear properties of a material. Two-photon absorption cross-section values of commercial PI's, such as Irgacure 369 (Ciba), 4,4'-Bis(diethylamino) benzophenone (Sigma) and many others were measured. Femtosecond Yb:KGW (515 nm, 300 fs) and Ti:Sapphire (800 nm, 20 fs) lasers were used in the fabrication process. Biocompatible hybrid organic-inorganic materials (custom made zirconium-containing sol-gel and commercial material ORMOCER, Micro Resist Technology GmbH) and biodegradable polylactide-based photopolymer were used to build 3D porous artificial matrices. Example structures such as cardiovascular grafts with appropriate scale for surgical practice were fabricated up to several millimeters in size, had 40-60 % porosity and 40-100 μm pores. Preliminary results indicate a good adhesion of pre-osteoblastic cells on the polylactide-based material compared to the control glass surface, and an increase in cell proliferation after several days. This suggests suitable applications in bone tissue engineering. Finally, DLW with picosecond laser (Nd:YVO, 532 nm, 8-25 ps, 0.2-1 MHz) was investigated reducing technological costs and opening opportunities for practical applications. Resolution dependence on pulse duration and pulse repetition rate were carried out, as well as quality and fidelity of photopolymerization were compared. Within the limitation of our interdisciplinary study, we conclude that the proposed direct laser writing technique offers rapid and flexible fabrication of biomedical components with required shape, pore size and general porosity.

8427-117, Poster Session

Clinical measurements with multi-spectral photoplethysmography sensors

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A newly developed portable multi-spectral photoplethysmography (MS-PPG) optical sensor device intended for analysis of peripheral blood volume pulsations at different vascular depths has been designed and clinically tested. Multi-spectral monitoring was performed by means of a four - wavelengths (465 nm, 530 nm, 630 nm and 870 nm) light emitted diodes and a single photodiode with multi-channel signal output processing. Two such sensors can be operated in parallel. The laboratory and clinical tests (3 patients so far) confirmed ability to detect

PPG signals at four wavelengths simultaneously and to record temporal differences in the signal shapes (corresponding to different penetration depths) in normal and pathological skin. The proposed methodology and potential clinical applications in dermatology for skin assessment are discussed.

8427-118, Poster Session

Analysis of porous polymer scaffolds for cells cultivation with confocal microscopy

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At the present time porous scaffolds based on polylactide (PL) are widely used in tissue engineering. Different methods are applied for preparing these scaffolds depending on their application. One of these methods is phase separation of two polymers hence remove one of them by selective dissolution or resorption. Recently scientists are very interested in methods for preparing porous scaffolds using polylactide (PL) and polyethileneoxide (PEO) blends.

These porous scaffolds are hydrophobic and they lack sites for cell adhesion, for this reason it is very important to modify these scaffolds using extracellular proteins mainly collagen I in order to make them hospitable for cell cultivation. The aim of this research was to study structure of porous scaffolds prepared with amorphous poly(d,l-lactide) and polyethileneoxide (PEO) blend, their modification using collagen I and assessment of cell cultivation on these modified scaffolds. Material and methods: Polymer scaffolds were prepared by dissolution 500 g polymer mixture poly(d,l-lactide) and 10 or 30 % polyethileneoxide in 15 ml methilyne chloride. Polymer scaffolds were analyzed by Confocal microscopy, Atom-force microscopy and Scan electronic microscopy. The scaffolds structure, collagen distribution on polymer surface and cells morphology were analyzed by confocal microscopy.

Results and conclusion: Obtained porous scaffolds in the form of polymer films, thickness of 15 and 50 µm. Obtained polymer films with uniform structure and monomodal pores. These films were prepared from 30 % PEO with molecular weight 6000. The pore sizes are not more than 5-6 µm. Demonstrated a microscopic cross section of polymer films consist of different concentrations of PEO. Pores were spread among the whole surface. Microscopic analysis showed that quantity and size of pores depend on the concentration of PEO. Film surface which consists of 10 % PEO with molecular weight 6000, have pores of 1 µm in diameter and their quantity is less than those found on the film surface which consists of 30 % PEO (molecular weight 15000), the size of pores were 1 to 10 µm. Porous and solid films were modified using collagen I with concentration 0.1 g/ . Modified porous polymer films with collagen I enhance fibroblast adhesion to the surface of the scaffold.

8427-119, Poster Session

Non-linear optical imaging and fibre-based spectroscopy of fresh colon biopsies

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Non-linear optical (NLO) microscopy is a widely diffused tool to deeply image human tissues without any exogenously added probe. NLO microscopy can take advantage of the autofluorescence of molecules intrinsically contained in a biological tissue, as such NADH, elastin, collagen, and flavins. NLO microscopy has been already successfully used to image several types of tissues, including skin, muscles, tendons, bladder, and others. Nevertheless, its usefulness in imaging human colon tissue has not been deeply investigated yet. In this work we have used different NLO microscopy techniques, including two-photon excited fluorescence (TPEF), second harmonic generation microscopy (SHG), fluorescence lifetime imaging microscopy (FLIM), and multispectral two-photon emission detection (MTPE) to investigate different kinds of human ex-vivo fresh biopsies of colon. Morphological and spectroscopic analyses allowed to characterize both healthy tissue, polyp, and colon cancer samples in a good agreement with common routine histology. In particular, we observed morphological differences between healthy tissue, polyp, and cancer on the basis of the nuclear-to-cellular dimensional ratio. Cancer and polyp cells appear with larger nuclei with respect to corresponding healthy cells, allowing for the discrimination between different tissue types. In addition, spectral lifetime imaging analysis allowed to discriminate tissues on the basis of the NADH and FAD mean fluorescence lifetime. Finally, fibre-based spectroscopy was used for a fast and reliable analysis of the tissue by means of fluorescence-Raman spectroscopy measurements. The obtained results can be easily transferred in vivo since the two fibre-probe used are properly sized to be inserted in the service channel of a colonoscope. Even if further analysis, as well as a more significant statistics on a large number of samples would be helpful to discriminate between low, mild, and high grade cancer, our method is a promising tool to be used as diagnostic confirmation of histological results, as well as a diagnostic tool in a multiphoton endoscope or colonoscope to be used in in-vivo imaging applications.

8427-120, Poster Session

RGB imaging system for monitoring of skin vascular malformation’s laser therapy

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Vascular malformation’s laser therapy can be monitored by assessing hemoglobin concentration and oxygen level changes. Multi-spectral imaging (MSI) is a suitable non-contact technology, but the commercial multi-spectral imaging systems are bulky and expensive, so limiting their clinical implementation. Color digital camera can be regarded as an alternative, acquiring three spectral images (red (R), green (G) and blue (B)) simultaneously. In combination with specific narrow-band spectral light sources, R-G-B imaging could become competitive for some specific applications, including the mapping of skin chromophores.

A prototype RGB imaging system for mapping of skin chromophores consists of a commercial RGB CMOS sensor, RGB LEDs ring-light illuminator and orthogonally orientated polarizers for reducing specular reflectance. The system was used for monitoring of vascular malformations therapy.20 vascular malformations (angiomas and port wine stains) were treated with 810 nm laser and monitored before and after treatment. Oxygenation level decrease was observed in the laser therapy target area and increase in the surrounding tissue due to skin irritation after treatment. The initial results showed that RGB imaging system is well suited for evaluation of skin condition after treatment or surgery.

8427-121, Poster Session

Full-range spectral domain optical coherence tomography using fiber-based sample scanner as self-phase shifter

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We propose full-range spectral domain optical coherence tomography (SD-OCT) with a fiber-based sample scanner, which is used for both sample scanning and phase shifting at the same time. In a fiber-based sample scanner, since the fiber tip oscillates as a free standing cantilever in general, unintentional phase shift occurs inevitably. It means that the focal line of the line scanner is not linear but more like parabolic which gives phase offset in the lateral direction while scanning. Generally, the scan in the shape of parabola is considered as a drawback to fiber-based scanners such as optical aberration and image distortion. However, from a positive perspective, it can be used as a phase shifter to eliminate the bothersome complex conjugate ghost image of OCT. In this scheme, moreover, image can be obtained without any physical modification of the scanner. Specifically, we adopt BM mode scanning method as one of full-range methods. However, in our experiment, the phase modulation of a reference beam (M scan) is performed in the sample arm as well with lateral sample scanning (B scan). Then, the rest of post signal processing is same as BM scanning method. To realize this technique, we constructed the SD-OCT system and fabricated a magnetically actuated single-body lensed fiber scanner due to advantages of simple design, low operating voltage, cost-effectiveness and low insertion loss. The scanner was made of lensed fiber loaded with an iron-based bead and a solenoid which is placed perpendicular to the lensed fiber. When a sinusoidal current is applied into the solenoid, the lensed fiber oscillated due to magnetic force between the iron-based bead and the solenoid. With the suggested full range method, we obtained contrast enhanced full-range SD-OCT images of pearls. This simple and effective method can be applied to any fiber-based scanner and it has great potential as a handheld probe/endoscopic probe in biomedical imaging field.

8427-122, Poster Session

Waveguide-type localized plasmon resonance biosensor for noninvasive glucose concentration detection

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Surface plasmon resonance (SPR) is a very sensitive technique for determining small refractive index changes at the interface between a metallic layer and a dielectric medium (analyte) [1]. Localized plasmon resonance (LPR) based structures in opposite to SPR have less sensitivity but good advantages for designing of high efficiency, low-cost, waveguide-compatible, and minimal consumption of analytes biosensors.

For LPR structures fabrication we use patented technology of silver nanoparticles (NPs) formation in photothermorefractive (PTR) glasses [2]. The size, shape and concentration of NPs precipitated in a glass subsurface layer depend on glass composition, intensity irradiation (UV, electron etc.) and thermal treatment. The HRTEM image shows that the shape of NPs is close to the spherical ones and the estimated NP diameters are distributed between 5-10 nm. The particles distribute in discrete layers with different width. The optical properties of obtained structures are investigated in relation to different dozes of electron beam irradiation and thermal treatment conditions. The optimal treatment process leads to appearing of the LPR peak at 410-420 nm.

Immobilization of D-glucose/D-galactose binding protein (GGBP) on top of PTR glass as a glucose biosensor test was realized successfully. The fluorescence enhancement in range 540-630 nm in presence of D-glucose was obtained in acrylodan dye with GGBP-W183C and strong fluorescence enhancement in a wide range 400-700 nm in badan dye with GGBP-H152C.

It was also shown the elaborated technology has a good applicability for plane waveguide and fiber biosensors based on LPR in metal nanoparticles.

References

1. Reather H (1988) Surface plasmons on smooth and rough surfaces and on gratings, vol. 111. Springer, Berlin Heidelberg New York.

2. A. V. Vostokov et al, Technical Physics Letters, 35(17), 58-63 (2009).

8427-123, Poster Session

Magnetic particles for sequence-specific DNA detection

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Magnetic beads are frequently employed in various bioassays. Their wide spread field of application includes isolation and purification of biomolecules like nucleic acids, proteins or cells as well as medical applications like targeted drug delivery or magnetic resonance imaging. We could recently show that magnetic beads are a useful tool for multiplex detection of PCR products by means of SERS (Surface Enhanced Raman spectroscopy). [1] The combination of SERS and magnetic beads has certain advantages over other methods for sequence specific DNA detection. For example real time PCR (Polymerase Chain Reaction) has only limited multiplexing possibilities. Also, fluorescence labels might be subject to photobleaching or quenching. SERS detection avoids these problems and offers excellent potential for multiplexing since each molecule has a specific fingerprint region and the bandwidth of vibrational modes is small.

In this study we used different immobilization techniques for modification of nano- and micrometer sized magnetic beads with single stranded DNA and subsequently performed hybridization experiments with dye labeled complementary oligonucleotides. Our approach has not only been tested with synthetic oligonucleotides, but moreover with PCR products. Furthermore the compatibility of different SERS substrates with magnetic beads has been investigated.

[1] K. K. Strelau et al. J. Raman Spectrosc. 2011, 42, 243-250.

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8427-124, Poster Session

Supercontinuum laser based double-integrating-sphere system for measuring optical properties of highly dense turbid media in the 1300-2350 nm region with high sensitivity

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Accurate knowledge of the optical properties of turbid media in the light path is important in NIR absorption spectroscopy of biological tissues where multiple scattering complexes the collected light signals due to the non-uniform tissue architecture. Several approaches, such as time resolved spectroscopy and spatially resolved spectroscopy have been proposed to measure the bulk optical properties of turbid media. Among them, double integrating sphere (DIS) measurements are recognized as the “golden standard” for in vitro optical properties measurement of turbid media, because of its high accuracy and robustness in different conditions. A DIS system is convenient to measure the in vitro optical properties of turbid media like intralipid solutions and biological tissues, since it measures the diffuse reflectance and transmittance simultaneously. However, DIS measurements have been mostly limited to the optical window region (400-950 nm) or suffered from low signal levels on the detectors due to the absorption by water in the NIR region. In this study, we developed a DIS system with high sensitivity in the 1300-2350 nm region based on a novel wavelength tunable light source which incorporates a high power supercontinuum laser and a high precision monochromator. With this system, optical properties of liquid phantoms and animal tissues were measured in the wavelength region 1,300 nm -2,350nm. The system’s sensitivity was investigated through probing the changes in optical properties of intralipid phantom caused by concentration variation.

8427-125, Poster Session

Ultrahigh resolution full-field optical coherence microscopy with multiple light-emitting diodes

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Optical coherence tomography (OCT) is an imaging technique that relies on interference of low-coherence light. The axial resolution in OCT is determined by both the central wavelength and the spectral bandwidth of the light source. For a given central wavelength, a larger spectral bandwidth enables a higher axial resolution. However, dispersion occurring in the imaged sample becomes an issue at large imaging depths. This has the effect of degrading the axial resolution and causing a signal fall-off with imaging depth. Depending on the imaging depth that is dictated by an application, it may be more appropriate to choose a light source with a narrower spectral bandwidth so that the axial resolution and the OCT signal do not degrade significantly with depth.

A full-field OCT (FFOCT) system is presented as an alternative to conventional OCT for ultrahigh resolution imaging. The initial system design has a halogen lamp source emitting an effective spectral bandwidth of 300 nm centered at a wavelength of 750 nm. The system was modified to incorporate a series of light-emitting diodes (LED) with different emission spectra so that the effective spectral bandwidth of emission is 115 nm centered at a wavelength of 820 nm. Compared to the halogen source, the LED-based light source enables an axial resolution and a signal strength that degrade less with depth. The illumination efficiency is higher. The electric consumption is lower. Thermal effects due to infrared radiation are not as detrimental for the sample. The LED-based source is robust and can be operated in a pulsed regime potentially enabling in vivo applications.

The effect of dispersion caused by a sample on the image quality is discussed. The LED-based FFOCT system is described. Imaging results showing the improvement of image quality with depth are shown.

8427-126, Poster Session

A multimodal holographic system for optical injection and manipulation of developing embryos

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Transgenic animals are an essential means for investigating genetic processes in vivo, and depend on efficient delivery techniques to introduce exogenous genetic material into the organism, often at the zygote stage. Conventionally, DNA microinjection is the method of choice in genetic modification of embryos. The embryo is held by negative pressure using a pipette, and a fine glass microinjector is used to deliver picolitre volumes of genetic material. However, this method is intrusive, and requires both experience and manual dexterity to be performed successfully. In this study, we demonstrate an optical approach to microinjection based on a holographic system using a spatial light modulator and a Ti: Sapphire laser. This integrated system is capable of both optical orientation and injection of 60-μm diameter Pomatoceros lamarckii (P.lamarckii) embryos. Individual blastomeres of P. lamarckii embryos were optoinjected with varying sizes of dextran molecules and Propidium iodide using an 800nm femtosecond laser with controlled dosage. We also show that the technique is able to deliver materials to cells located deep within a well-developed embryo without damaging overlying cells. As a visual confirmation of successful optoinjection, the presence of gas bubbles was observed as a function of laser power and exposure time. Small gas bubbles, less than 5-μm in diameter, were found to be tolerated by the irradiated embryo. Furthermore, when switched to the continuous wave mode, the laser could exert optical forces upon the embryo. This facilitated computer-controlled handling and orientation of P. lamarckii embryos without compromising viability. Our multimodal optical platform offers a sterile, non-contact and robust alternative to traditional microinjection. This work is a step towards applications in developmental biology such as cell lineage mapping and formation of transgenic animals using an optical approach.

8427-127, Poster Session

Propagation, structural similarity index, and image quality

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Retinal image quality is usually analysed through different parameters typical from instrumental optics, i.e, PSF, MTF and wavefront aberrations. Although these parameters are important, they are hard to translate to visual quality parameters since human vision exhibits some tolerance to certain aberrations. This is particularly important in post-surgery eyes, where non-common aberration are induced and their effects on the final image quality is not clear.

Natural images usually show a strong dependency between one point and it neighbourhood. This fact helps to the image interpretation and should be considered when determining the final image quality. The aim of this work is to propose an objective index which allows comparing natural images on the retina and from them obtain relevant information abut the visual quality of a particular subject.

To this end we propose a individual eye modelling. The morphological data the subject's eye is considered and the light propagation through the ocular media is calculated by means of a Fourier-transform-based method. The retinal PSF so obtained is convolved with the natural scene under consideration and image obtained is compared with the ideal one by using the structural similarity index. The technique is applied on 4 eyes with a multifocal corneal profile (Presbylasik) in order to determine the real extension of the pseudoaccomodation achieved.

8427-128, Poster Session

AFM and SEM imaging in low vacuum conditions of new drug delivery nanosystems

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The last decades, with the rapid development of the nanotechnology, a revolutionary growth of alternative methods have been proposed using nanosystems and nanomolecular carriers for cancer treatment. Gold and ceramic nanoparticles, quantum dots, nanotubules, liposomes and dendrimers have been examined as drug delivery systems in nanomedicine and pharmaceutical technology. Among them, liposomes are the most attractive lipid vesicles. They are spherical structures composed of one or more lipid bilayers which enclose aqueous space(s). Liposomes are presently being used as carrier and delivery agents for a great variety of molecules including drugs, enzymes and dyes due to their high loading capacity and their flexibility to accommodate photosensitizers with variable physicochemical properties.

Recently, in the research field of drug delivery, chimeric advanced drug delivery nanosystems (Chi-aDDnSs) combining liposomal and dendritic materials have been appeared. They offer numerous advantages over the conventional drug delivery systems including high drug loading, controlled release and a large variety of carrier materials and manufacturing processes. A relatively young class of dendritic polymers, named hyper-branched polymers (HBPs), has lately attracted much research attention and their effectiveness in replacing dendrimers as HBPs is characterized by a high degree of branching, a three-dimensional architecture, and multiple terminal functional units.

Nanosystems characterization is an important issue and many analytical techniques are employed for studying their characteristics. Among them Scanning Electron Microscopy (SEM) in low vacuum and Atomic Force Microscopy (AFM) are powerful analytical techniques producing high-resolution images of a surface. In our work we used these microscopy techniques in order to study the morphology, dynamics and stability of Chi-aDDnSs. In this study, polyol hyperbranched polymers have been employed along with liposomes for the preparation of new chi-aDDnSs. The observation of the sample was not required special treatments as gold or metal coat, which induce irreversibly change or damage of the sample. The shape and the size of chi-aDDnSs were observed by AFM. The micromechanical properties of chi-aDDnSs were studied by using AFM since it is allows force-deformation measurements of submicron nanoparticles. Interesting dynamic shape deformations were noticed in nanometric scale by SEM. Budding transitions and fissions of Chi-aDDnSs were observed which mimic cellular processes.

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References

1. R. Dhankhar, S.P. Vyas, A.K. Jain, S. Arora, G. Rath, A.K. Goyal, Advances in Novel Drug Delivery Strategies for Breast Cancer Therapy, Artif. Cells Blood Substit. Biotechnol. 38 (2010) 230-249.

2. K. Gardikis, C. Tsimplouli, K. Dimas, M. Micha-Screttas, C. Demetzos, New chimeric advanced Drug Delivery nanosystems (chi-aDDnSs) as Doxorubicin carriers, Int. J. Pharm. 402 (2010) 231-237.

3. E. Spyratou, E.A. Mourelatou, M. Makropoulou and C. Demetzos, “Atomic force microscopy: a tool to study the structure, dynamics and stability of liposomal drug delivery systems”, Expert Opinion on Drug Delivery, March 2009, Vol. 6, No. 3: 305-317.

8427-129, Poster Session

Development of portable non-contact photoplethysmography device

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Photoplethysmography (PPG) is an optical monitoring method that provides information about relative blood vessel volume changes at each heartbeat. A new portable device at the size of ordinary mobile phone for non-contact PPG measurements has been developed. The device is capable of real-time heart rate measurements from the distance up to 1m. Additional parameters opening possibility to construct skin perfusion map can be obtained. This device also has a potential in recording of blood oxygenation changes and multispectral examination of skin diseases. All the measurements and calculations are being done on controller of the device, without external computer.

The device consists of five main modules - CMOS image sensor, LED array (450nm, 545nm, 660nm, 940nm), LCD, memory and controller that connect all the modules together.

The device was examined for monitoring of physiological responses during specific provocation - arterial/venous occlusions.

8427-130, Poster Session

Miniature wireless photoplethysmography devices: integration in garments and test measurements

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Wearable optical health monitoring sensors integrated into telemedicine and mobile systems represent a novel biophotonic technology for early detection of abnormal cardiovascular conditions. A mini-device for photoplethysmography (PPG) signal detection has been developed and integrated in smart-wear prototypes. Recent designs of wireless photoplethysmography monitoring devices embedded in wrist cuff, glove, bandana and scarf, Bluetooth-connected to PC, are described. First results of distant monitoring of heart rate and pulse wave transit time using the newly developed devices are presented.

The main components of the garment-integrated devices are: PPG sensor, a central system control unit, a Li-ion accumulator and Bluetooth transmitter module. The developed wireless PPG sensor incorporates GaAs emitting diode (peak wavelength 940 nm) and Si photodiode. Bluetooth module is capable to transmit real-time signals within 10 m surrounding area.

Test measurements of heart rate by comparison with professional ECG device have been performed. Potential future applications can be shape analysis of human arterial pulse waves and detection of specific vascular malfunctions.

8427-131, Poster Session

Influence of low power CW laser irradiation on skin hemoglobin changes

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The aim of this study is to evaluate influence of low-power laser irradiation on skin chromophore changes that have been previously observed as autofluorescence photo-bleaching. Using multispectral camera and fiber-optic spectrometer, the spectral changes in healthy skin diffuse reflectance were registered after irradiation by cw low-power 405nm, 473nm and 532nm lasers (power densities of the range 30 to 100 mW/cm2). The halogen lamp has been used as a broadband source for diffuse reflectance measurements. After the irradiation, changes in diffuse reflectance spectra in the range 500nm - 600nm have been observed, leading to conclusion that the content of skin hemoglobin has changed. Further studies of this phenomenon are in progress.

8427-132, Poster Session

Physiological state influence to skin autofluorescence photobleaching

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In-vivo skin autofluorescence under continuous low power laser irradiation has been studied to deeper understand influence of different physiological conditions to the autofluorescence photobleaching. Measurements were taken from healthy skin of 4 volunteers by examining the effects of increased and reduced temperature, arterial occlusion, skin humidity, presence of skin cream and other factors. Autofluorescence spectra were recorded by fiber optic spectrometry set at continuous 473 nm and 532 nm laser irradiation with power densities below 100 mW/cm2. The measurement results confirmed sensitivity of the photobleaching rates to physiological state of skin. For instance, during the post-occlusion overshoot substantial increase of the photobleaching rate was observed for all examined persons at both laser excitations. The results show that selected physiological state combinations may influence specific skin responses to low-power laser irradiation.

8427-133, Poster Session

Microscopic control of cell viability in a biocarrier

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Inoculation of the synthesized materials into organism damaged area during transplantation often leads to homeostasis disorder and, as consequence, to inability of long functioning of an inoculated synthetic matrix. These phenomena are difficult to predict at the stage of graft production therefore noninvasive monitoring method of cell integration into a graft allowing estimating its quality is necessary.

For graft viable cell revealing and viable cell distribution visualization the confocal fluorescence microscopy method on the base of inverted microscope Olympus IX 71, confocal scanner Yokogawa CSU-1 with EMCCD camera iXon Andor were used in the study. This system allowed reaching resolution of 400 nm/ pixel. Fluorescence was generated with use of the laser unit providing generation capacity up to 100 mW at wavelengths of 488 nm and 561 nm.

Demineralized spongiosis and fibroblast-like cells grown from a hyaline costal cartilage, used for degrading joint treatment by prosthesis, were used as a graft under study. The use of Cy3 phosphoramide derivatives, excited by laser radiation at wavelength of 561 nm, has allowed to increase cell image contrast to 0,8-0,9 and to detect cellular structure development in real time. Root-mean-square speed of osteoblast movement was 7-8 μm/h. Level-by-level scanning of the GFP dyed transplant showed viable cells in its structure throughout the experiment. The analysis of the received micrographs allows drawing a conclusion that cells penetrate the graft, spreading mainly over its internal surface and forming a “colony” near the implant pores on the surface. On the eighth day the active osteoblast density is already 500-700 cell/mm2.

8427-134, Poster Session

Study of magnetotactic bacteria interaction with magnetic field using digital holographic microscopy

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Digital holographic microscopy provides a non-destructive and quantitative phase contrast imaging that is suitable for marker-free high resolving investigations of living cells and organelles. In this paper we utilize this technique to study the dynamic morphological changes of magnetotactic bacteria membrane in presence of a time varying magnetic field. In a controlled experiment using a microinjecting pump the movement of a single or a set of bacteria are monitored live and successive digital holograms are recorded. Magnetotactic bacteria are a polyphyletic group of motile, aquatic prokaryotes bacteria, that orient along the magnetic field lines. To perform this task, these bacteria have organelles called magnetosomes that contain magnetic crystals. In contrast to the magnetoception of animals, the bacteria contain fixed magnets that force the bacteria into alignment-even dead cells align. Bacteria have different membrane structures and the structural differences lie in the organization of a key component of the membrane, peptidoglycan. These elongated bacteria are propelled by single flagella at each bacterial end and contain a magnetic filament. The movements of the bacteria in suspension are analyzed by consideration of the orientation of their magnetic dipoles in the field, the hydrodynamic resistance of the bacteria, and the propulsive force of the flagella. The magnetic moment of individual living magnetic bacteria can be determined by motion analysis and morphology change detection in a time-dependent magnetic field. We collect Living magnetotactic bacteria from small lakes in Zanjan area and keep them under steady laboratory conditions. The method we use provides precise investigation of morphology change effects of the bacteria. The recorded holograms by CCD can be post-processed to three dimensional reconstruction of the samples. We have used angular spectrum propagation method to reconstruct the complex wave fields in the experiments. The quantitative structural changes in various interacting time of the bacteria with magnetic field is extracted by analyzing of the recorded digital holograms.

8427-135, Poster Session

Single-layer reduced graphene oxide based SPR biochips for tuberculosis bacillus detection

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In this study, we present an immunosensing application of a novel single-layer rGO/Au-based biosensor for the detection of a tuberculosis bacillus (TB). The sensitivity of TB detection in diluted pleural fluid samples was determined by an single-layer rGO/Au thin film SPR and compared with that of a conventional Au/Cr-based SPR biosensor. Surface roughness and specificity of the sensor systems were also evaluated. The results show that an rGO/Au SPR offers a potentially powerful assay, with a highly sensitive analysis, that may be applicable as an important tool for bio-marker detection. Most important of all, we combined with the surface plasmon resonance (SPR) to real-time monitoring the thickness of single layer rGO. The variation of rGO can be controlled by SPR technology, lead rGO back into the best structure. Therefore, tuberculosis bacillus was investigated as an analytical model with a novel thin film-based SPR device.

From this technology, we can get the best structure of rGO which have great biocompatible properties. The biological cells can further born on it and inhibit the growth of the bacterial. The purpose of combination SPR technology is that it has excellent ability for surface analysis, high sensitivity for oxygen refractive coefficient, and the ability for real-time detection, so it is a new kind of electrode materials with potential applications in electrochemical sensing and SPR biosensing.

8427-136, Poster Session

Development of a non-invasive multispectral LED device for adipose tissue thickness measurements in vivo

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There are a number of techniques for body composition assessment in clinics and in field-surveys, but in both cases the applied methods have advantages and disadvantages. High precision imaging methods are available, though costly and non-portable, however, those methods devised for the mass population often suffer from the lack of precision. Therefore, the development of a safe, mobile, non-invasive, optical method that would be easy to perform, precise and low-cost, but also offers the accurate assessment of subcutaneous adipose tissue (SAT) both in lean and in obese persons is required. Thereof, the diffuse optical spectroscopy is advantageous over the aforementioned techniques.

A new prototype device using a multispectral method for measurement of the SAT thickness in vivo has been developed. The probe contained different wavelengths LEDs (670nm, 770nm, 870nm, 940nm) distributed at various distances from the photo-detector which allow different light penetration depths into the subcutaneous tissue.

The differences of the reflected light intensities (DC component) were used to create a non-linear model, and the computed values were compared with the corresponding thicknesses of SAT, assessed by B-mode ultrasonography.

The experimental outcome confirms that with the optical system used in this study, accurate results of different SAT thicknesses can be obtained, and implies a further potential for employment of multispectral optical systems to observe changes of SAT thickness as well as to determine the percentage of total body fat.

8427-137, Poster Session

The effects of pressure in determination of position and size of the tumor of biological phantoms

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Due to the expansion of laser's application in medicine for diagnostic and therapeutic purposes, the study of light propagation in tissue has achieved a significant prominence. Penetration depth, absorption and chemical interactions of light with micro organelles and living micro molecules inside the medium are the most important issues while considering the interaction of light and tissue. Absorption coefficient and scattering coefficient are the most notable parameters regarding the absorption and penetration depth of light. These two parameters describe the propagation of light in tissue. Propagation of light and its penetration depth differ considerably between different parts of the body. The reason for this fact is that different tissues in the body have dissimilar absorption and scattering coefficients. Therefore, the measurement of absorption and scattering coefficients and determination of the factors which might influence these two parameters, appear to be essential. Information about these factors should be available while using lasers in medicine.

Pressure is one of the factors which are predicted to influence these two important parameters. Application of lasers in different branches of medicine such as surgery, ophthalmology, laser hair removal and optical imaging is usually accompanied by pressure applied to the tissue. While performing optical imaging, the pressure which is applied by the imaging device might cause variations in absorption and scattering coefficients of the tissue. This might cause errors in determination of depth and size of the tumor. As a result, obtaining a quantitative perspective of the effects of pressure on optical properties of tissue can be beneficial to modification of this error.

In this study the effect of pressure on optical properties of tissue-like phantoms is investigated. Phantoms are placed inside the optical imaging setup and the intensity of light exiting the outer boundaries of the sample is measured. Subsequently, appropriate pressure is applied on the sample and the measurement procedure is repeated. After the experiments are carried out, the variations in absorption and scattering coefficients of the phantom are obtained via solving the diffusion equation in a simulated medium similar to the phantom. The diffusion equation is solved by the finite element method code. Subsequently, phantoms possessing a defect are constructed. The defects, which represent a tumor in cancerous tissues, have optical properties similar to tumors. The effect of pressure in determination of position and size of the defects is studied quantitatively and the error in tomography which is caused by the pressure is modified.

8427-138, Poster Session

FTIR characterization of animal lung cells: normal and precancerous modified e10 cell line

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The chemical carcinogens from tobacco are related to over 90% of lung cancers around the world. The risk of death of this kind of cancer is high because the diagnosis usually is made only in advanced stages. Therefore, it is necessary to develop new diagnostic methods for detecting the lung cancer in earlier stages. The Fourier Transform Infrared Spectroscopy (FTIR) can offer high sensibility and accuracy to detect the minimal chemical changes into the biological sample. The aim of this study is to evaluate the differences on infrared spectra between normal lung cells and precancerous lung cells transformed by NNK (4-(methylnitrosamino)-1-(3-pyridyl1)-1-butanone). Non-cancerous lung cell line e10 (ATCC,Rockville, MD, USA) and NNK-transformed e10 cell lines were maintained in complete culture medium (1:1 mixture of Dulbecco's modified Eagle's medium and Ham's F12 [DMEM/Ham's F12], supplemented with 100 ng/ml cholera enterotoxin, 10 lg/ml insulin, 0.5 lg/ml. hydrocortisol, 20 ng/ml epidermal growth factor, and 5% horse serum) (Life Technologies, Rockville, MD, USA). The cultures were maintained in PBS. The infrared spectra were acquired on ATR-FTIR Nicollet 6700 (Thermo Scientific Nicolet, Waltham, MA) spectrophotometer at 4 cm−1 resolution, 30 scans, in the 1800-900 cm−1 spectral range. 10 µl of cell solution was placed on the ATR diamond crystal, and dried with air during 5 min before spectrum measurement. Each samples had 3 spectra recorded. Seventy infrared spectra were obtained from each cell line. The Principal Components Analysis (PCA) indicates that main modifications on the spectra occur in the follows wavenumbers: 1045 cm-1 (C-O stretching), 878 cm-1 (DNA-form helix conformation), 1273 cm-1 (phosphate) and 1455 cm-1 (proteins, amino-acids). These preliminary results indicate that ATR-FTIR spectroscopy is useful to differentiate normal e10 lung cells from precancerous e10 transformed by NNK lung cells. The results suggest that FTIR spectroscopy can be used in the future for diagnosis of early stage lung cancer in smoking population. Acknowledgements: Financial support FAPESP CEPID (05/51689-2), Instituto Nacional de Fotônica/CNPq (573.916/2008-0), CNPq (143166/2009-3).

8427-139, Poster Session

Corneal topography reinterpretation through separate analysis of the projected rings

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We present a new algorithm to process captured images of reflected Placido rings. Up to our knowledge, conventional topographers transform from Cartesian to polar coordinates and vice-versa thus extrapolating corneal data and introducing noise and image artefacts. Moreover, captured data are processed by the device according proprietary algorithms and offering a final map of corneal curvature. Corneal topography images consists of concentric rings of approximately elliptical shape. Our proposal consists of considering each separate ring. The information is reconstructed by using a snake-annealing method which permits identifying the ring even with discontinuities due to eye-lashes and reflections.

By analysing the rings geometrical parameters (centre, semi-axis and orientation) one can obtain information about small morphological micro-fluctuations and local astigmatisms. These parameters can be obtained with subpixel accuracy so the method results of high precision. The method can be easily adapted to work on any topographer, so that it can provide additional information about the cornea at no additional cost.

8427-140, Poster Session

In vivo real-time monitoring of nanoparticle clearance rate from blood circulation using high speed flow cytometry

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The rapidly growing application of nanotechnology in medicine has placed new demands on monitoring clearance rate of nanoparticles with different shape, composition, and conjugation from systematic circulation. No clinically relevant method has been developed for rapid and ultrasensitive detection of nanoparticle clearance rate at single nanoparticle levels. We introduce a new laser-nanotechnology based platform for in vivo real-time monitoring of nanoparticles using advanced high speed multicolor photoacoustic flow cytometry (PAFC). As most nanoparticles have intrinsic absorption, PAFC is an almost ideal tool for real-time, label-free monitoring of nanoparticle pharmacokinetics. We used four colors to verify the concept of in vivo multicolor PAFC, but the potential exists to increase the number of spectral channels. The capability of this platform was demonstrated on blood circulation of animal models for detection of magnetic nanobeads and gold nanorods of different size and conjugations. The advantages and limitations of the new technique were discussed.

8427-141, Poster Session

Real-time monitoring of nanoparticle-cell interaction using photothermal and photoacoustic cytometry

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Evolving applications of nanotechnology in medicine have significantly increased demands for real-time monitoring and detection of nanoparticles and nanoparticle-cell interactions, both in vivo and in vitro, with varying flow conditions. In particular, we examine the efficiency of tumor cell targeting using conjugated nanoparticles, not absorbed by "normal" cells (a critical characteristic for selective cancer diagnosis and therapy). Using our robust photothermal and photoacoustic assays, which provide rapid assessment of nanoparticle-cell interactions with nonfluorescent nanoparticles (e.g. gold or magnetic), at the single-cellular level, our technology possesses the capacity to detect nanoparticle-cell association as well as dissociation over time. Our approach provides a level of sensitivity unobtainable from conventional microscopy-including detection of single nanoparticles attached to cellular membranes. We demonstrate the capabilities of these methods for monitoring selective labeling of MDA-MB-231 human breast cancer cells in blood using multicolor gold nanorods with functionalized antibodies against specific biomarkers (e.g. folate, EpCAM, etc.), which are dominantly expressed in cancer cells.

8427-142, Poster Session

Multispectral imaging and identification of chromophores in bacteria, live cells, and C. elegans using confocal photothermal spectromicroscopy

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Recent advances of photothermal microscopy include detection of strongly absorbing single nanoparticle and molecule detection under ideal low scattering conditions. In natural biological background photothermal detection has to operate under conditions of strong absorption and scattering background. The existing photothermal schematics either have limited sensitivity in such samples or are limited by the low axial resolution. The use of single wavelength lasers or of the lasers tunable in a narrow range seriously limits spectral identification of multiple chromophores.

Herewith, we describe photothermal spectromicroscopy platform combining confocal thermal-lens detection scheme optimized for highly scattering biological specimens with a robust single-photon excitation in a wide spectral range. Confocal detection of the probe beam modulation by the photothermal element dramatically improves axial resolution of the method and permits ultra-local absorbance detection. The integrated system provides confocal 2D and 3D imaging and identification of chromophores and nanoparticles in bacteria, live cells and C.Elegans. We demonstrated volume reconstruction of absorbance distribution on the base of the photothermal imaging.

The use of tunable excitation laser provides opportunities for multispectral imaging and identification in an extremely wide spectral range, 420-2200 nm, with a signal being acquired from an ultra-local diffraction limited sample volume.

The new platform was verified for high-resolution 3D imaging and identification of multiple (up to 4) chromophores and fluorophores at a single cell level including C. elegans studies. Examples include cytochrome c, intrinsic and genetically engineered melanin, fluorescent proteins, light absorbing and fluorescent nanoparticles. Light absorption contrast could provide a valuable supplement to fluorescence microscopy, for imaging of nonfluorescent chromophores and fluorophores, respectively.

8427-143, Poster Session

Optimal irradiation condition of demineralized dentin treatment with a nanosecond pulsed laser at 5.8 μm wavelength range

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[Background] Some mid-infrared lasers, for example Er:YAG laser and Er,Cr:YSGG laser, have already realized the optical drilling of dental hard tissue in dental clinic. Although the selective excavation of carious dentin is required, conventional lasers cannot treat a carious dentin only because they use the laser tissue interaction derived from a strong absorption of water. Based on the absorption property of carious dentin, a wavelength range around 6 μm is a candidate for selective excavation. Our group has already observed the difference of ablation depth between demineralized and normal dentin (selective excavation) in 6 μm wavelength range. In 6 μm wavelength range, the wavelengths around 5.8 μm have a potential for minimally invasive treatment of demineralized dentin. Objective of this study is to determine the optimal irradiation condition for the selective excavation by using a wavelength around 5.8 μm. [Material and Method] Bovine dentin demineralized by soaking in lactic acid solution was used as a carious dentin model. A nanosecond pulsed laser in the wavelength range from 5.6 μm to 6.0 μm was obtained by difference-frequency generation technique. The laser delivers 5 ns pulse width at a repetition rate of 10 Hz. After irradiation, morphological change and ablation depth were observed with a scanning electron microscope and a confocal laser microscope, respectively. Adhesion test was also conducted to confirm the adhesion level between an irradiated dentin surface and a dental composite resin. [Results] In 5.8 μm wavelength range, a short wavelength (5.6-5.75 μm) required high excavation energy and a long wavelength (5.8-5.9 μm) required low excavation energy to induce the selective excavation with a low thermal side effect. 6 μm also showed the selective excavation, but the irradiation condition was limited. There was no significant difference between 5.8 μm and 6.0 μm in the result of adhesion test. [Conclusion] The irradiation condition with the wavelength around 5.8 μm was determined. A wavelength around 5.8 μm provides a selective excavation of deminelarized dentin for minimal intervention.

8427-144, Poster Session

The effects of diode pumping YLF: Er laser radiation on hard tooth tissues

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Today Er-lasers with wavelengths near 3 microns are widely applied to treatment of hard tooth tissue. The wavelengths are close to peaks of enamel and dentine absorption. YLF: Er laser irradiates in wavelengths range of 2.6-2.9 μm. Diode laser radiation was used for YLF: Er crystal pumping in this work. Advantages of diode pumping of YLF: Er laser are: possibility of more effectively conversion of pumping energy to generation energy; simple change of wavelength, pulse duration, pulse repetition rate and spatial distribution. In this work enamel and dentine treatment was carried out by YLF: Er laser radiation with wavelength of 2.84 µm, at single-pulse impact. Pulse energy reached 2 mJ in treated area at pulse duration of 150-300 µs, 3.5 mJ at pulse duration of 300-700 µs, and 4.5 mJ at pulse duration of 700-1000 µs. We observed some effects as a result of laser radiation impact: modification (whitening), destruction (crater formation) and carbonization. Modification (whitening) of enamel was observed at pulse energy of 0.5-1.4 mJ and pulse duration of 270-955 µs. This effect was observed for dentine at 0.4-0.7 mJ and 270-930 µs. Enamel destruction occurred at pulse energy of 1.1-2.2 mJ and pulse duration of 285-980 µs. This effect was observed for dentine at 0.8-1 mJ and 280-940 µs. Enamel carbonization was not observed at impact of YLF: Er laser radiation. Dentine carbonization was observed at pulse energy of 1.6-2.2 mJ and pulse duration of 300-980 µs.

8427-145, Poster Session

Development of a biochip scanner based on laser confocal scanning technology

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We have developed a biochip detection instruments based on laser confocal scanning technology. The biochip scanner's character is keeping optical system immovability while a biochip moving in a plane vertical the optical axis or laser input ray, so it holds an excellent performance. Working 3.22mm up the biochip, the optical system for the biochip scanner has been designed into microscopic imaging mode with a laser focusing object lens and a fluorescence focusing ocular lens. The object lens can focus a laser beam into a spot less than 10um on the biochip. A sensitive photomultiplier tube is used to make sure the dynamic detection range of 106 to monitoring the fluorescence induced by input laser from the biochip. The biochip is fixed on a 2-dimensional moving stage which is driven by a linear motor and a step motor and controlled by TMS320LF2407 with proportion integration differentiation (PID) algorithm. The precision guide, ball screw shaft, motors and grating ruler together guarantee the 2-dimensional stage moving in scope of 20mm width and 60mm length. The scanning time for 20mm*60mm is within 6 minutes with scanning resolution of less than 5um. Application software is user's interface friendly and easy programmed by c/c++ language in windows operation system. The biochip's fluorescence signal collection and motion control are communicated with a personal computer through USB protocol. The experiment results show that our developing instrument has realized the scanning scope of 20mm*60mm within 6 minutes and with a resolution of less 10um.

8427-146, Poster Session

Photodynamic inactivation with Zn(II), Pd(II), and Ni(II) phthalocyanines of periodontal pathogen aggregatibacter actinomycetemcomitans planktonic and biofilm cultured

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Antimicrobial photodynamic therapy (aPDT) is based on the uptake of photosensitizing agents by microbial cells, followed up by a proper light irradiation in order to produce singlet oxygen and other reactive oxygen species, which cause cell death. Antimicrobial PDT has a number of advantages in comparison to the traditional antimicrobial method due to the lack of observations for bacterial resistance. In the recent years the PDT as a method for antimicrobial treatment was applied successfully against a number of oral pathogens. In same time the effect of aPDT to the anaerobic periodontal pathogens is not yet well studied. To understand which mechanism of inactivation of anaerobic strains play main role in PDT, it is necessary to separate effect of O2 in environment medium from effect of applied photosensitizer. Therefore the influence of photothermal therapy (PTT) on bacteria, which is still not explored, will be given additional information for mechanism of inactivation.

The aim of the study is to evaluate the ability of photodynamic sensitizers (PSs) like ZnPcMe and PdPc and a photothermal sensitizer NiPc to produce antimicrobial effect against the Aggregatibacter actinomycetemcomitans (A. actinomycetemcomitans), which is the main pathogen in aggressive periodontitis.

Bacterial strain: Aggregatibacter actinomycetemcomitans (Gram-negative, microaerophilic pathogen, involved in periodontal infections, including gingivitis and periodontitis) was cultured in planktonic cultures and biofilm on polymethylmethacrylate (PMMC) discs by using Tryptic Soy Broth. The dark toxicity to the used photosensitizers (ZnPcMe, PdPc and NiPc) was determined at treatment concentrations (1-7 µM). The PDT studies were carried out in comparison to three control groups of bacteria: only with PSs (dark toxicity), only with light and only bacterial suspension. Two light sources were used namely LED at 635 nm and Diode laser at 660 nm. Three photosensitizers were applied, one methylpyridyloxy-substituted Zn(II) and two unsubstituted Pd(II) and Ni(II)-phthalocyanines.

Full inhibition (5 log reduction of bacterial cells) was achived after 25 min irradiation with red light of bacteria as planktonic cultures after 7 µM Zn(II)-phthalocyanine. At the same treatment protocol the reduction efficiency of Pd(II)-phthalocyanines was approximately 4 log. The bactericidal effect was negligible after with Ni(II)-phthalocyanine bacterial cells. The biofilms of A. actinomycetemcomitans cultured on PMMC can be successfully inactivated at strong PDT conditions or by combining actions of PDT and PTT. The affectivity of inactivation in this case was less that observed in planktonic culture.

The photodynamically effective photosensitizer ZnPcMe and PdPc , irradiated whit proper parameters of light, demonstrate a pronounced antimicrobial effect on A. actinomycetemcomitans planktonic and biofilm cultures.

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8427-147, Poster Session

Stereomicroscopic evaluation of the articular cartilage and bone tissue in osteoporosis

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Aim of the study. Assessment by stereomicroscopy of the severity of lesions in osteoporotic bone at both sexes and to correlate micro-and macro-bone fracture due to low bone density values with the disease evolution.

Matherial and Method: The study material consists of fragments of bone from the femoral head, vertebral bone, costal and iliac crest biopsy obtained from patients aged over 70 years, female and male, treated in the County Hospital of Timisoara, Department of Orthopedics. For the purpose of studying the samples in stereomicroscopy and trough polarized light it has been used the Olympus Microscope SZ ×7 and an Olympus camera with 2,5 × digital zoom and a 3× optical zoom in the Vest Politechnic Univesity.

Results and discutions: Subchondral bone presents osteolysis associated with a osteoporotic bone transformation. Pseudocystic chondrolisis was noted in the osteoarticular cartilage, in addition with areas of hemorrhagic postfractural necrosis. The osteoporotic bone exhibits ischemic necrosis and focal hemorrhagic necrosis adjacent fracture. Microporosity pattern of the bone observed by stereomicroscopy correspond to the spongy bone osteoporosis images. Morphometry of the bone spiculi reveals length of 154.88 and 498.32 µ. In men we found a greater thickness

of bone trabeculi compared with bone texture porosity in women. The subchondral bone supports and fulfills an important role in transmitting forces from the overlying articular cartilage inducing the bone resorbtion.

The femoral head fracture may be the final event of many accumulated bone microcracks.

Conclusions: Bone fragility depends not only of the spongy bone but also of the cortical bone properties. Osteolysis produced by loss of balance in the process of remodeling in favor of bone resorption leads to the thinning of the subchondral bone at both sexes.

8427-148, Poster Session

Femtosecond irradiation of chicken corneas analyzed by digital holographic microscopy

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Digital Holographic Microscopy (DHM) is a potentially non-invasive new technology which can be applied in many areas from applied imaging science to biomedical optics. DHM is an interferometric technique that gives us a number of important advantages such as the possibility to acquire holograms at high speed, to obtain complete information about amplitude and phase and to use image processing techniques. In this sense, DHM offers rapid 3D imaging with a theoretically higher resolution than OCT (Optical Coherent Tomography). By this technique optical path measurements with sensitivities in the nanometer range of reflective and transparent objects can be obtained.

In this work, we use DHM to study the effect of ablation by 4.5 nJ pulses on chicken corneas. For this, a titanium sapphire laser at 800 nm and 76 MHz frequency (Vitesse, Coherent Inc. USA) was focused to its diffraction-limited spot size by a 10x objective of 0.3 numerical aperture. The width of the pulse at the sample was measured by spectral techniques and it was 170 fs. The average beam power at the sample was 340 mW and the whole system was mechanically driven by a XY synchronisation unit that controlled the speed of the sample movement. The speed of the sample varied between 1-50 micron/s.

The chicken corneal tissue studied was previously processed by Trypan dye in order to visualize the irradiated area. The photodisrupted zone was analyzed by a HDM technique by illuminating it using a laser diode source (wavelength of 683 nm) linearly polarized in a modified Mach-Zehnder with an off-axis geometry configuration. The reflected object wave on the tissue surface (specimen) interferes with the reference wave and a CCD camera records the hologram. As a result, the influence of the speed of photodisruption in the depth of the ablated corneas was analyzed. Therefore, it is possible to analyze thermal and photoirradiated effect on corneal tissues which allows us the possibility to optimize the interaction of intratissue and intratissue target region of interest.

8427-149, Poster Session

Stereomicroscopic study of the human tooth caries: clinical and morphological correlations

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Objectives: The stereomicroscopy permits the three-dimensional study of the images and of laterality with superior quality in comparison with other methods. Those advantages are given by the large examination fields and the wide work distances. The adding of the clinical and morphological dates at the results gathered with stereomicroscopy and the stereo micrometry is useful in order to appreciate the profundity and the widening of the carious process, the necessity to reconsider the therapeutical strategy.

Materials and methods: During 2009-2011 the study material was represented by 10 tertian impacted molars, surgically removed and by 20 premolars extracted orthodontic and with closed surfaces for this purpose with apparently integer macroscopically surfaces. There has also been selected 13 parodontical premolars with different grades of carious affectation witch were extracted surgically without trauma. The in situ measurements at the occlusion situ were realized trough the utilization of the fluorescent laser dispositive DIAGNOdent. The base principles in stereomicroscopy stood at the base of the coaxial illumination techniques, obliquely and inellary one with optical adjustment of the alignment of the optical microscope and mechanical for the optimal illumination and micrometry. For the purpose of studying the samples in stereomicroscopy and trough polarized light it has been used the Olympus Microscope SZ ×7 and an Olympus camera with 2,5 × digital zoom and a 3× optical zoom.

Results: In the DiagnoDent we have revealed the next: from the 43 apparently healthy tooth: 18 presented values between 2 and 13 (D1), 13 with values between 14 and 20 (D2), 12 with values over 20 (D3). After the histological examinization in stereomicroscopy and in the polarized light: 25 teeth were healthy, 10 presented caries of the dental enamel and 8 presented dentinal caries. The stereomicroscopy has permitted the morphological study, the color absorption, the appreciation of the profundity of the substance loss that is very useful in grading the progression of the carious lesion.

Conclusions: The stereomicroscopic study correlated with clinical and morphological data has permitted to appreciate the surface of the tissue involved in the carious process, but also the understanding of the matricial demineralization process in the enamel, dentine and the cementus in proximity with the morpho-embriological markings of the human tooth structure.

8427-150, Poster Session

Electronomicroscopic evaluation of the microlesional aspects in the pulp dentinal complex after repeated whitening therapy

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The aim of this study was to examine cellular and matriceal dynamics within pulp tissue of the teeth with repeated bleaching.

Material and method - The study was made on 25 patients aged between 15 and 45, to whom bleaching method of the premolars with indication of extraction in orthodontic purposes was applied. None of the subjects smoked and throughout the investigation no antibiotics had been used. We initiated an intensive oral hygiene programm, and we removed the supragingival and subgingival deposits. Oral hygiene and the gingival health were evaluated before every session of bleaching. During each visit the dentition was cleaned professionally and if needed the subjects were reinstucted in proper oral hygiene. After 3 and 5 successive bleachings of the teeth, we removed the dental pulps and we extracted the premolars. The pulpal biopsies were fixed in buffed formaldehyde 10% for 48 hours, then paraffinized, sectioned at 3-5 µ and stained with topographic, H&E and trichrome stained. For the electonomicroscopic study we used the Lehner technique to process the biopsies (n=3) after the reinclusion of the pieces from the paraffine blocks in Epon, postfixated in buffered glutaraldehyde, micro sectioned at o,5 µ, contrastated with Pb citrate (stained) and examination in transmission electronic microscopy with Philips microscope.

Results -At cellular and matricial level we observed a marked collagen fibrillogenesis in the presence of active fibroblasts, with well developed cellular organites and fibroclastic aspects which suggest matriceal active repair.

The microvascular network presents an activated endothelium with turgescent endothelial cells, with intracitoplasmatic resorbtion vacuols, well developed Golgi Complex.

Conclusion - We interpretated the cell - matriceal lesions in the context of the acute inflammatory process in the first lesional phase and chronic scleroatrophic process after successive bleaching.

8427-151, Poster Session

Size and photostable effect of gold nanoparticles in dual-modality photodynamic and photothermal therapy

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In this work, we have described the preparation and characterization of gold nanoparticle-coated indocyanine green (ICG) as well as a study on the stability of the photosensitizers coated on gold nanomaterials. Further, we also demonstrated that the gold nanoparticle-coated ICG can still maintain its photostability even via higher temperatures mediated by laser irradiation, resulting the combination of photodynamic therapy (PDT) and photothermal therapy (PTT) proved to be efficiently ablating cancer cells as compared to PDT or PTT treatment alone and enhanced the effectiveness of photodestruction and acting as a promising diagnostic probe. Moreover, the photochemical destruction ability would have a gradually increase depending on different sizes of gold nanoparticles. As a result, the preparation of gold nanoparticles conjugated with photosensitizers as well as their use in biomedical applications is valuable developments in multifunctional nanomaterials.

8427-152, Poster Session

Effects of the position of Galactose substituents to Zn(II) phthalocyanines on the fluorescence detection and photodynamic activities towards breast cancer cells

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Photodynamic therapy (PDT) is well accepted as curative method for non-invasive fluorescent diagnosis and local treatment of tumors. PDT consists of the common action of three constituents: a photosensitizer (PS) which has to localize in the tumor cells, the proper light within the PS absorbance and the molecular oxygen surrounding. As a result a singlet excited state of PS forms, which can relax to the singlet ground state by fluorescence emission and/or by non-radiative transitions. Fluorescence pathway of energy decay utilizes in the photodiagnosis of human tumors. In competition the energy transfer to the triplet state of PS initiates photochemical reactions with the atmospheric oxygen and the cellular membranes. The generated singlet oxygen and other reactive oxygen species are toxic to the cells and are causing the selective tumor photodamage.

The substantial knowledge has been collected about the structure-activity relation for the screening as PDT sensitizers. The understanding that the glucose transporters are overexpressed in tumor cells and are functionally involved in the receptor-mediated signaling processes has been explored for the new drug design strategy of PDT sensitizers. The natural carbohydrates have a specific recognition sites on cancer cells where numerous types of glucose transporters have been expressed. The suitable substitution of hydrophobic phthalocyanine improves the solubility and may perhaps minimize the aggregation tendency.

Herein, we report the synthesis of Zn(II)-phthalocyanines with four D-galactose moieties linked to the macrocycle via oxygen on the non-peripheral (3,6) or the peripheral (4,5) positions. The subcellular localization of GalPcs was studied for two human breast cancer cell lines (MCF-7 and MDA-MB-231). The effects of the position of the substituents of GalPcs as compared to non-substituted ZnPc on the uptake, the subcellular localization and the photodynamic activity were studied.

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8427-153, Poster Session

Photodynamic therapy with water-soluble phtalocyanines against bacterial biofilms in teeth root canals

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The neutralization of influence of microbial biofilms in the endodontic pathology by a conventional antibiotic therapy is problematic due to a rapidly growth of antibiotic resistance and a intrinsic for bacterial biofilms mechanisms for protection. The photodynamic therapy (PDT) approach is recently proposed for effective treatment of pathogenic microorganisms. PDT appears the only alternative in cases of multi-drug resistant strains and biofilms.

The study presents the PDT with metal phthalocyanines on biofilms grown in root canals of ten representatives of the Gram-positive and the Gram-negative bacterial species and a fungus Candida albicans which cause aqute teeth infections in root canals..

The extracted human single-root teeth infected for 48 h with microorganisms in conditions to form biofilms of the above pathogens were PDT treated. The stage of biofilm formation and PDT effect of the samples of the teeth were determined by the scaning electron microscopy and with standard microbial tests. The PDT treating procedure included 10 min incubation with the respected phthalocyanine and irradiated with 660 nm Diode laser for 10 min.

The most strongly antibacterial activity was achieved with zinc(II) phthalocyanine (ZnPc) against Enterococcus faecalis, Staphylococcus aureus and Moraxella catarrhalis. The other Gram-negative bacteria and Candida albicans were 10-100 times more resistant than the Gram-positive species. The Gram-negative Moraxella catarrhalis and Acinetobacter baumannii were more sensitive than the enterobacteria, but eradication of Pseudomonas aeruginosa in biofilm was insignificant. The influence of the stage of biofilm formation and the initial conditions (bacterial density, photosensitizer concentration and energy fluence of radiation) to the obtained level of inactivation of biofilms was investigated.

The PDT with ZnPc photosensitizers show a powerful antimicrobial activity against the most frequent pathogens in endodontic infections and this method for inactivation of pathogens may be used with sucsses for treatment of the bacterial biofilms in the root canals.

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8427-154, Poster Session

Characterization and differentiation of leukocyte sub populations in blood using micro-Raman spectroscopy

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The first response of the body to any abnormal physiological condition is mediated by the immune system. The immune system comprises of different populations of cell types, among which the leukocytes play a significant role. The conventional method for detection of various diseases such as infection is by determining a differential blood count

by means of blood smears and/or fluorescence-activated cell sorting (FACS). The blood smears are gold standard but are time consuming and dependent on the assessor. Whereas FACS is cost-intensive and some of the physiological information of the leukocytes is lost. For an immediate diagnostic it is very important to have quick information on the leukocyte sub population along with their respective biochemical information.

Raman spectroscopy has proven track record of its ability to differentiate between different cell types, such as normal and cancerous cells [1, 2], for the analysis of clinical relevant bacterial cells from body fluid [3] and in many other biomedical areas. In this study the potential of Raman spectroscopy will be exploited as a new diagnostic tool for investigating the ratio of different leukocyte populations such as monocytes, granulocytes and lymphocytes without the need of any staining methods. Leukocytes from healthy volunteers were separated from erythrocytes by means of cytolysis. The leukocytes suspended in plasma were coated on CaF2 slides by means of cytospin and Raman measurements were carried out using NIR laser with 785 nm as excitation wavelength. Supervised and unsupervised statistical methods are applied to achieve a differentiation between the types of leukocytes.

1. Neugebauer, U., Clement, H: J.; Bocklitz, T, Krafft, C:, & Popp, J., J. Biophoton, 3 (2010) 579-587.

2. Dochow, S., Krafft, C., Neugebauer, U., Bocklitz, T., Henkel, T., Mayer, G., Albert, J., & Popp, J., Lab Chip, 11 (2011) 1484-1490.

3. Harz, M., Kiehntopf, M., Stöckel, S., Rösch, P., Deufel, T., & Popp, J., Analyst, 133 (2008) 1416-1423.

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8427-155, Poster Session

Photonic crystal fibers for food quality analysis

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Hollow core photonic crystal fibers provide high sensitivity to the optical parameters of a medium, filling up a hollow core of the fiber, e.g. refractive index and absorption coefficient. By making only one measurement one can obtain both, optical density value (in determined spectral range) and refractive index of a tested liquid. In a purpose of providing precise analysis of multicomponent liquid solutions, photonic crystal fiber may become a tool of a big efficiency. One of the possible applications of PCF-based optical sensors is considered in this work. The use of photonic crystal fibers allows one to make a complex analysis of different drinks like juices, vines, etc. In our investigation we considered the influence of sugar and iron, which are the most important components of an apple juice, to spectral properties of hollow core PCFs. Thus, we considered an ability of application of hollow core photonic crystal fibers in food quality analysis.

8427-156, Poster Session

Monitoring of the microhemodynamic in an aggressive clinical behavior of cerebral hemorrhage using dynamic light scattering techniques

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Monitoring of the microcirculation dynamics is one of the possible diagnostic tools for various cardiac diseases and accompanying structural changes. Detecting micro-vascular and hemodynamic pathology can help in making proper medical decisions at diagnostic and treatment stages. The results of experimental study of cerebral monitoring of microcirculation using spatial laser speckle contrast analysis technique (sLASCA) are presented. For further measurement of blood flow have been using methods of digital microscopy and Doppler techniques. Microcirculation dynamics in cerebral was investigated by using a heavy stress influence, which leads to the formation of cerebral hemorrhage. Experimental data was collected and processed at 50 iterations per second with averaging over 10x10 pixel region of brain for 20 labaratory rats. Additional optical clearing agent (80% water solution of propylene glycol with dimethylsulfooxide (dmso)) was also used to increase method sensitivity by eliminating high scattering in cranium.

8427-157, Poster Session

Photo-induced fat cell porosity and lipolysis

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The effect of optical properties changes of adipose tissue slices in vitro as a result of photochemical action was found and investigated. The 100-150 m fat tissues slices were used in in vitro experiments. Water-ethanol solutions of indocyanine green (ICG) and brilliant green (BG) of 1 mg/ml and 6 mg/ml concentration, respectively, were used for fat tissue staining. CW laser diode (ACCULASER, 810 nm) and dental diode irradiator Ultra Lume Led 5 (442 and 597 nm) were used for irradiation of tissue slices. Laser irradiation time was 1 min, and the diode lamp 5 min. The studies were conducted at room temperature. After photochemical action the transillumination images of a sample were registered by digital microscope periodically with the period of 5 - 10 min. These images demonstrate the dynamics of transillumination of the sensitized fatty tissue induced by light irradiation.

The computer processing of the obtained high resolution digital images gave an opportunity to find cell membrane porosity as a result of photochemical action and cytoplasm release from a cell. It was proved that the phenomenon observed is related to the lipolysis of adipose tissue cells.

8427-158, Poster Session

Description and activities of the Biophotonics4Life International Consortium

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We will describe the Biophotonics4Life International Consortium which involves 21 nodes or centers of activity in countries worldwide. The consortium meets regularly, hosts an international congress every year, creates strategic road maps and generally, determines who is doing what and where in biophotonics. Mor information is readily available at http://biophotonicsworld.org.

8427-159, Poster Session

Simulation of electrophysical properties of biological tissues by the intracavity laser spectroscopy method

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A mathematic model is constructed for predicting the absorption spectrum and dispersion of a section of a biological structure consisting of epidermis, upper layer of the derma, blood, and lower layer of the derma and placed in the cavity of an optical resonator. The quantitative estimates obtained here can be used for predicting changes in the optical properties of the sample of the biological tissue under investigation associated with various biophysical and biochemical processes in this sample.

8427-64, Session 13

Infrared microscopic studies to understand the effect of drugs at molecular level

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Fourier Transform Infrared (FTIR) microscopic study, on the effect of chemotherapeutic drugs on cancer cells and also on hepatotoxicity induced by acetaminophen (APAP) in mouse model, is presnted in this paper. Histone deacetylase inhibitors (HDACi) are known as potential drugs for the treatment of cancer. These are chemotherapeutic drugs which have indirect mechanistic action against histone deacetylases (HDAC) (1-3) in cancer cells. Therefore, to optimise chemotherapy, it is important to determine the efficacy of various classes of HDAC inhibitor drugs against variety of over-expressed HDAC enzymes. FTIR microscopy has been used to monitor chemical changes (4), such as, acetylation and propionylation, induced in a series of cell lines using many different drugs. Remarkable changes have been observed for various drugs, depending on the type of cell lines. The results indicate a very good correlation of the efficacy of drugs with the chemical changes induced in histone proteins by HDACi, which is also supprted by biochemical assay results.

In the second part, the FTIR study of biochemical changes induced by APAP overdose on liver would be presented. Acetaminophen (APAP) is a widely prescribed drug used to relieve pain and fever. However, it is a leading cause of drug-induced liver injury (DILI) and a burden on public healthcare. In this study, APAP-induced hepatotoxicity in mice was investigated using IR microscopy. In the spectra of APAP treated livers the ratios of the infrared band intensities at 1030 cm-1/1080 cm-1, 1171 cm-1/1152 cm-1 and 966 cm-1/996 cm-1 were found to change, indicating decrease in glycogen, increase in amounts of cholesteryl esters and DNA respectively. Interestingly, the rescue experiments using pre- or post- treatment with L-methionine (L-met) confirms the above observation. Importantly, the serum IR spectra identified lowering of glycogen and increase in DNA earlier than increase in alanine aminotransferase (ALT), which is routinely used in diagnosis of liver damage. This study raises the possibility of using FTIR analysis of sera as a rapid and non-invasive alternative to rise in ALT amounts or biopsies to detect liver damage. Overall, this study supports the growing potential of FTIR microscopy as a fast, highly sensitive and label-free technique for non-invasive diagnosis of liver damage.

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REFERENCES

1. Jessica E. Bolden, Melissa J. Peart and Ricky W. Johnstone, Nature Reviews(Drug Discovery) 5, 769-784 (2006).

2. Milos Dokmanovic, Cathy Clarke, and Paul A. Marks, Mol Cancer Res 5, 981-989 (2007)

3. Paul A. Marks, Victoria M. Richon and Richard A. Rifkind, Journal of the National Cancer Institute 92, 1210-1216 (2000)

4. Tsoching Chen, Min-Jung Lee, Yeong Sang Kim, Sunmin Lee, Shivaani Kummar, Martin Gutierrez, Stephen M. Hewitt, Jane B. Trepel, and Ira W. Levin, Analytical Chemistry 80, 6390-6396 (2008).

5. Larson, M. A., Polson, J., Fontana, J. R., Davern J. T., Lalani E., Hynan S. L., Reisch S. J., Schiødt V. F., Ostapowicz G., Shakil O. A., Lee M. W., Hepatology. 42, 1364-1372 (2005).

6. Holt, P. M., Cheng, L., and Cynthia Ju. Journal of Leukocyte Biology. 84, 1410-1421 (2008).

7. Podshyvalov, A., Sahu, K. R., Mark, S., Kantarovich, K., Guterman, H., Goldstein, J., Jagannathan, R., Argov, S., and Mordechaiv, S. Applied Optics. 44, 3725-3734 (2005).

8. Toyran, N., Lasch, P., Naumann, D., Turan, B., and Severcan, F. (2006) Biochem. J. 397, 427-436 (2006).

8427-65, Session 13

Label-free multimodal microspectroscopic differentiation of glioblastoma tumor model cell lines by means of multivariate data analysis

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Glioblastoma multiforme represents the most common malignant brain tumor in adults. The mean survival time after diagnosis is only a few months. The extreme malignancy is caused by inactive tumor suppressor genes PTEN and TP53. A tumor model has been developed based on the U-251 MG cell line from a human explant. The tumor model simulates different malignancies by controlled expression of the tumor suppressor proteins PTEN and TP53 within the cell lines derived from the wild type. Cells with at least one active tumor suppressor gene are less malignant and represent the possible beginning of a tumor development. The cells from each different malignant cell line were grown on quartz slides for UV/VIS microspectrophotometry and on calcium fluoride slides for micro IR spectroscopy. A paraformaldehyde fixation was applied followed by a drying step. All UV/VIS- and IR-spectra were recorded in the cell nucleus. The spectral preprocessing for the multivariate data analysis (MVA) consisted of a smoothing step, a baseline correction, a normalization and a mean centering. In the case of the UV/VIS spectra an additional derivation was applied. For the differentiation of the cell lines a principal component analysis (PCA) was performed. The PCA demonstrates a good separation of the tumor model cell lines both with UV/VIS spectroscopy and with IR spectroscopy. We show that in UV/VIS spectroscopy the combination of the absorption in the UV with the scattering information in the VIS-region improves the differentiation between the cell lines. With the sensitive and label-free stray light microscopy, it will be possible to detect changes in the morphology of the cell structure even in nanoscale due to Mie-scatter-interference. We further propose with the help of a multivariate curve resolution a spectral assignment of the chemical cell components.

8427-66, Session 13

Sensor design for cancer tissue diagnostics

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In this study a metamaterial-based sensor operating in the THz frequency range is presented.

The sensor is designed to detect the difference of cancerous tissue from the normal one by permittivity and spectral absorption measurements.

The resonance of the sensor is designed to coincide with the water spectral characteristics to recognize its presence. A malignant tissue has a significantly higher water content compared to normal tissues. Water shows a peak in the absorption spectrum in the THz frequency range.

When the resonance of the sensor is close to that of the material under test, the shape of the response is greatly modified (especially in terms of amplitude width) because of the strong absorption. This due to the fact that all organic molecular species absorb in certain spectral regions and the characteristic spectrum depends on the corresponding molecular structure.

A change in the frequency amplitude of the sensor response is related to the different water content in the organic material under study, allowing to distinguish healthy tissue from the cancerous one.

In addition the sensor behavior is connected to another phenomenon.

The alteration of the entire structure permittivity, caused by the presence of the biological compound, produce a change in the frequency tip position.

From the resonant frequency position of the system “sensor-biological material” and the peak widening, it is possible to determine the stage of the disease.

In particular full-wave simulations show that the sensor can be successfully used to detect healthy and cancerous tissues with high selectivity and sensitivity with the ability to distinguish the various disease stages.

The designed system is also suitable to be used for calculating the water rate content, with other possible applications in medical diagnostics.

8427-67, Session 13

Recent advances of in vivo flow cytometry

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In vivo flow cytometry is a novel research tool for noninvasive monitoring of circulating nanoparticles (NPs), normal and abnormal cells (e.g., tumor cells or bacteria), directly in the blood flow in natural biological environments. This report summarizes our recent advances of this technology by the integration of in vivo photoacoustic (PA) flow cytometry (PAFC) with Raman detection methods, multicolor laser arrays, multifunctional nanoprobes and high speed signal acquisition algorithms. As a result, we developed a clinically-relevant platform for real-time detection of biomolecules, dyes, NPs and individual single cells with targeting of multiple biomarkers. This platform can operate noninvasively using, either microscopic or fiber-based schematics, for delivery laser radiation in two basic detection modes: label-free and nanotechnology-based labeling of circulating objects . By combining the laser with high pulse rate (up to 0.5-1 MHz), ultrahigh sensitivity and deep penetration in biotissues (up to 5 cm), our PAFC-based platform overcomes the limitations of existing methods. The capabilities of integrated in vivo flow cytometry were demonstrated using preclinical animal models of human breast cancer, metastatic melanoma, myocardial infarction and human sickle disease, as well as, using human blood samples. We showed ultrasensitive detection of circulating tumor cells including tumor-initiating cancer stem cells in the blood and lymph flows, circulating and adhered clots with sizes down to 20 µm and multiple determinants of blood rheology. The power of our technology also includes detection of cell morphology (e.g., clustering of intracellular hemoglobin, specific shape of sickle RBCs), cell functions (e.g., trafficking, aggregation, apoptosis, and necrosis) and cell signaling (e.g., expression of specific receptors). We extended the application of PAFC for analysis of bones. The assessment of entire blood volume (potentially 5 L in human) may significantly (>100-fold) enhance the sensitivity of cellular and molecular diagnosis when compared to the existing clinical tests. Taking into account the safe nature of the proposed biotechnology, we anticipate its quick translation for use in humans to break down limit in early diagnosis, therapy and estimations of therapeutic efficacy of the most severe world-wide diseases such as cancer, heart attack and stroke.

8427-68, Session 13

Three-dimensional laser microfabrication of polymers for stem cell growth and tissue engineering applications

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In this report we present experimental results on laser microfabrication of three-dimensional polymer implants and study of their biocompatibility based on stem cell growth experiments in vitro as well as reaction of living organism to polymer implants in vivo. The systematic study of material laser structurability and material biocompatibility provides important information for further progress in controllable stem cell growth and tissue engineering.

In our laboratory, we used high pulse repetition rate amplified femtosecond laser system (280 fs, 200 kHz, 515 nm) and high sample translation velocity linear stages. The chosen materials were of several different classes: hybrid organic-inorganic polymers ORMOCER (Ormocore b59) and ORMOSILs (SZ2080 and custom made), di-acrylated poly(ethylene)glycol (PEG-DA-258) and poly(dimethylsiloxane) (PDMS). They were evaluated by their suitability for direct laser structuring, which is well established as a technique enabling rapid and flexible production of three-dimensional microstructured objects with higher than 1 µm spatial resolution and up to cm in overall size. The produced artificial scaffolds were with different desired pore sizes and porosities. Laser point-by-point direct writing and four beams interference lithography approaches were used to fabricate scaffolds with high throughput over a large area.

Additionally, the laser manufactured structures were tested as templates for replication via soft-lithography and hot-embossing approaches enabling rapid multiplication of identical samples required for the statistics of cell proliferation.

The produced scaffolds were tested in vitro (by growing stem cells) and subsequently in vivo (by implanting the scaffolds in the rabbit’s muscle for 3 weeks) for determination of their biocompatibility. In stem cell culture, all of the tested materials were of comparable biocompatibility to polystyrene substrate. Ex vivo histological examination showed their biocompatibility to be similar to a standard used surgical quote. Therefore, such scaffolds fabricated from the variety of polymer materials can be used for tissue engineering.

8427-69, Session 14

Fluorescent protein Killer-Red as a potential photosensitizer for PDT of cancer: a pilot animal study

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Photodynamic therapy (PDT) is a promising method for use in oncology. By now PDT has proved its efficacy against various types of cancer. A typical photosensitizer is a porphyrin derivative that is administrated intravenously or locally to accumulate preferentially in the tumor via enhanced permeability and retention effect. However, no ideal photosensitizer has been found so far. The existing chemicals have a

fairly low phototoxicity, weak selectivity to tumor cells and pronounced side effect such as phototoxic action on skin and mucosa. Recently it was discovered that a red fluorescent protein named KillerRed showed strong cell phototoxicity in vitro, and the phototoxicity depended greatly on its intracellular localization.

The aim of this study was to assess the possibility of PDT on mouse tumor xenographts with phototoxic protein KillerRed as genetically encoded photosensitizer.

The experiments have been performed on 15 female athymic nude mice with subcutaneously transplanted HeLa tumors (human cervical carcinoma). Stably transfected HeLa cell line expressing fluorescent protein KillerRed in nuclei and mitochondria has been used. PDT has been performed with a laser at 593 nm. Laser light was administered to the tumors for 30 min every day during 7 days. In the course of PDT a whole-body fluorescence imaging in vivo has been carried out. An accurate histological examination and electron microscopy of the tumors has been done to examine the subcellular effects of the therapy. To verify the distribution of the protein in the tumor tissue ex vivo confocal fluorescence microscopy has been used.

It has been established in vivo that the fluorescence intensity in the Killer-Red expressing tumors dropped immediately after the laser irradiation by 12 to 45% which indicated photobleaching of the fluorescent protein accompanying the photodynamic reaction. Then the signal remained at the same level over around two hours. Histopathological analyzis has revealed the essential differences between the treated and untreated tumors. Most cells in the treated samples showed significant vacuolization, broken plasma membrane or cariolemma. Some cells had small nucleus with a condensed chromatin in, while others had a huge swollen nucleus. On the electron microscopy images incomplete mitosis was found in the cancer cells.

In conclusion, this pilot animal study with KillerRed in tumors demonstrates that KillerRed can serve as a genetically encoded photosensitizer for PDT causing light-induced tumor destruction.

8427-70, Session 14

A compact handheld low-cost LED-based device for selective photocoagulation

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We have developed a compact, low-cost, and easy-to-handle photohaemostasis device for the reduction of bleeding from superficial capillary vessels. The working principle is based on the fact that blue light from a LED is selectively absorbed by the haemoglobin content of the blood and then converted into heat. In particular, in the violet-blue region of the spectrum (400-430 nm), the main absorber is haemoglobin. Thus, if a sample of blood is directly irradiated at these wavelengths, heat release can be induced in a blood layer of a few hundred microns, which correspond to the light penetration length. This temperature enhancement may finally result in a coagulation effect, depending on the emission characteristics of the light source. Recently, the development of a new class of LEDs with high-power, continuous-wave emission in the violet-blue spectrum may candidate these relatively low-cost light sources as an alternative to lasers, in order to induce blood photocoagulation. Here we firstly present a preliminary modeling study in which a Finite Element Model (FEM) of the LED-induced photothermal process has been implemented with the aim of estimating the optimal settings for the device in terms of wavelength, power density and treatment time. The model was used to study the temperature dynamics in the tissue due to blue light exposure and the results highlighted the possibility to selectively perform photocoagulation by taking advantage of the haemoglobin absorption in the 405nm-435nm range. Then we describe the handheld illumination device. This consist of a commercially available high power LED, emitting in the blue region of the spectrum, mounted in a suitable and ergonomic case, together with power supply, electronics, and batteries. The developed prototype was tested in the treatment of dorsal excoriations in rats. Thermal effects were monitored by an infrared thermocamera, experimentally evidencing the modest and confined heating effects and confirming the modeling predictions. Objective observations and histopathological analysis performed in a follow-up study showed no adverse reactions and no thermal damage in the treated areas and surrounding tissues. The device was then used in human patients, in order to stop bleeding during Erbium laser skin resurfacing procedure. By inducing LED-based photocoagulation, the overall treatment time was shortened and scar formation was reduced, thus enhancing esthetic effect of the laser procedure.

8427-71, Session 14

Minimally invasive combined laser surgery to perform corneal endothelium transplants in human patients

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The cornea is the optimal model tissue for the application of photonics based tools in surgery. An example is the use of the femtosecond laser for the resection of the corneal tissue, in clinical protocols such as LASIK or corneal transplant. We present an “all laser” technique, optimized for the transplant of the corneal endothelium, based on the combination of a femtosecond and a diode laser. The former is used for precise cutting of the inner portion of the cornea (the endothelial layer), both in the donor and recipient eyes. The near-infrared diode laser (810 nm) is used in pulsed mode to weld the transplanted tissue to the donor cornea. No alternative standard suturing techniques are nowadays available to the best of our knowledge in order to perform such a surgery in the anterior chamber of the eye. The procedures have been performed at the Public Hospital in Prato, Italy, in 30 selected patients: by the use of the femtosecond laser the surgeon prepared a 100 micrometer thick and 8.5 mm diameter donor endothelial flap (composed of the endothelium, the Descemet’s membrane and a some corneal stroma), as well as the corneal bed in the recipient eye. After staining the stromal layer of the donor flap with an ICG solution to enhance the absorption of the diode laser light, the flap was inserted in the recipient eye and laser-welded to the inside surface of the recipient cornea by means of 10 diode laser spots placed around its periphery. A satisfactory engraftment of the transplanted flap was observed in all the treated eyes. The OCT analysis in the follow up evidenced an immediate and effective welding at the interface of the donor/recipient tissues. The proposed technique was easy to perform and reduced to zero the risk of postoperative endothelial flap dislocations.

8427-72, Session 14

Laser reshaping of costal cartilage for ENT

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Laser reshaping of cartilage is a new effective and safe technique for correction of nasal septum and ear deformities. Costal cartilage is a most suitable natural material for transplantation. The problem is to obtain stable proper shape of cartilage implants.

The purpose of this work is to study a possibility and conditions of the laser reshaping of porcine costal cartilage to be used for transplantation in the larynx stenosis surgery. Conditions of laser correction of porcine costal cartilage are obtained. Nonlinear thermomechanical behavior of cartilage in the course of its laser reshaping is experimentally revealed. The influence of irradiation sequence on the curvature radius of cartilage implant is found for the first time. It is shown that (1) it is possible to use laser reshaping technique for making proper shape of costal cartilage,

and (2) primary irradiation of compressed side followed with an irradiation of stretched side is more effective than reverse sequence of laser treatment.

Porcine cartilage plates 3 mm in thickness were mechanically curved and irradiated (1) on one side (stretched or compressed) and (2) on both sides with different sequence. Irradiation was performed using a 1.56 microns laser with power varied from 1 to 2.5 W, exposure time from 5 to 20 s, spot diameter of 2.5 mm, pulse duration of 500 ms, pulse repetition rate of 1.4 Hz. For each laser setting, stable curvature radius was measured during 24 h after the experiment. Irradiated samples were analyzed by means of differential scanning calorimerty (DSC) to reveal the collagen denaturation degree.

The optimum laser setting for stable reshaping of costal cartilage without visual thermal damage of cartilage matrix was established. It is shown that (1) it is possible to use laser reshaping technique for making stable proper shape of costal cartilage, and (2) primary irradiation of compressed side followed with an irradiation of stretched side is more effective than reverse sequence of laser treatment. DSC analysis showed that thermal effect of irradiated specimens (2.58-3.79 J/g) was slightly lower that that for intact cartilage specimens and considerably lower than that for denaturation of collagen (65±5 J/g).

It is possible to use laser reshaping technique for preparation of stable cartilage implants. Nonlinear thermomechanical behavior of cartilage is experimentally revealed. The influence of irradiation sequence on curvature radius of cartilage grafts is established for the first time.

8427-73, Session 15

Toluidine blue O-conjugated gold nanoparticles for photodynamic therapy of cultured colon cancer

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Photodynamic therapy (PDT) is an emerging technique for the treatment of cancerous and non-cancerous conditions. In PDT, the light-activation of a photosensitizer leads to the generation of reactive oxygen species that can trigger various mechanisms of cell death. Toluidine Blue O (TBO), a cationic phenothiazinium dye, is a non-porphyrin PDT agent, which has previously shown photochemical and photophysical properties for photodynamic therapeutic application. Gold nanoparticles (GNPs) possess unique physical and chemical properties which allow them to act as multifunctional agents in nanomedicine. Gold nanoparticle-photosensitizer conjugates have attracted increasing attention in drug delivery for photodynamic cancer therapy. In the present investigation, we prepared covalent conjugates of the photosensitizer TBO and thiol protected GNPs. The conjugates were synthesized by carbodiimide-mediated (EDC) reaction, and characterized by ultraviolet-visible absorption spectroscopy (UV-Vis), transmission electron microscopy (TEM), FTIR spectroscopy, fluorescence spectroscopy, and X-ray photoelectron spectroscopy (XPS). The characterization data confirm the successful formation of GNPs-TBO conjugates. Near-infrared photoluminescence measurements provided evidence for an increased efficiency of singlet oxygen production by GNPs-TBO conjugates. High uptake rate of GNPs-TBO conjugates by the SW480 Human colon adenocarcinoma cell line was detected by TEM. The cells were subsequently photo-irradiated and PDT-induced cell death for various incubation periods was determined using a colorimetric assay. The results indicate that GNPs accelerated intracellular uptake of the photosensitizer with a consequent enhancement of the PDT-induced cytotoxicity with reduced time periods. Following PDT of the nanoparticle conjugates, flow cytometric analysis using Annexin-V assay revealed that these conjugates were effective at inducing apoptosis at high level. Our results suggest that gold nanoparticle conjugates are an excellent vehicle for delivery of photosensitizer agents in the photodynamic therapy of cultured tumour cells.

8427-74, Session 15

Cancer cells start to generate singlet oxygen once been triggered by 1268-nm laser irradiation: modeling oxidative stress mechanism

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Cancer remains an important health problem attracting attention of scientists in developing effective cancer treatment approaches. Expensiveness and in some cases (ionizing radiation) inconvenience of already existing cancer therapies have stimulated search of new solutions in curing cancer. One of popular approaches is photodynamic therapy (PDT) which relies on photodynamic effect of laser-excited photosensitises (PSs) stimulating singlet oxygen (1O2) production leading to cancer cell apoptosis. However general post-treatment phototoxicity of PSs limits PDT use. Recent development of quantum-dot (QD) laser diodes (LDs) emitting in the near infra-red (NIR) spectral range has opened up new venues in low-intensity laser therapy as well as in oncological photodynamic treatment. The LD emission centred at around 1.27 µm coincides well with the highest absorption of triplet oxygen molecule (3O2) enabling direct induction of oxidative stress in cancer cells through the 3O2→1O2 transition. Indeed observed photodecomposition of the 1O2 traps at 1268 nm suggests direct excitation of molecular oxygen and population of the singlet state at the irradiation doses and experimental conditions close to those conventionally used for biological experiments. Here we demonstrated that the NIR QD laser irradiation induced in HeLa, HaCaT, and primary keratinocytes (PK) loaded with dihydroethidium (DHE, superoxide anion (primary product of 1O2 oxygenation in water) sensitive fluorescent dye dihydroxiethium (product of DHE oxidation by superoxide anion) fluorescence, partially abolished by reactive oxygen species scavenger α-tocopherol. Further experiments with DHE on these cell lines showed that 1268 nm irradiation triggered dose-dependent 1O2 production in all of them with most dramatic effect on HeLa cells. The NIR laser irradiation dose of 119.4 J/cm2 demonstrated significant rise in cytosolic calcium concentration in both HeLa and HaCaT cell lines with higher effect on HaCaT. Parallel patch clam measurements of HaCaT cells showed increase in ion (Ca2+) channels activity suggesting that the NIR laser irradiation also activated plasma membrane Ca2+ channels. With the fact that f 1268 nm laser irradiation demonstrated strongest effect on HeLa cells we could say that by photo-excitation of molecular oxygen from ground state triplet state 3O2 to the excited singlet 1O2 with the NIR laser we triggered calcium-dependent ROS production in the cell making possible the idea of direct laser-induced cancer cell apoptosis. Based on the experimental results, a kinetic model of reactive oxygen species metabolism induced by the laser in the cancer and normal cells is also proposed.

8427-75, Session 15

In vitro efficacy of Ruthenium compounds in photodynamic therapy of cancer

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There is growing evidence that photodynamic therapy has high ability to suppress or destroy cancer cells. We assessed in vitro efficacy of new Ru-based photosensitizers (Ru-PS), Theralase Inc. (at a range of concentrations from 16 to 450 uM in culture medium) on three cell lines, comprising human colon cancer (HT-29), human glioblastoma (U-87) and rat glioma (F-98). Upon loading the photosensitizer (with or without removal of Ru-PS from the medium), photodynamic therapy (PDT) was conducted by irradiation of the cells with a green LED light (emitting 530 nm) at radiant exposure from 10 to 66 J cm-2. Cells viability after PDT

was measured by Presto Blue staining. PDT resulted in a strong decrease in cells viability exceeding 99% of the control values at 200-450 uM. Considerable PDT effect was observed at radiant exposures of 33 and 45 J cm-2. Removal of Ru-PS from the culture medium prior to irradiation (after incubation for 6 hours) did not diminish the effect of Ru-PS in combination with light exposure. The Ru-based photosensitizers currently under development by Theralase Inc. demonstrated a strong decrease in cells viability, >> 99% for multiple cell lines. Therefore, Theralase's Ru-PS may present rather promising properties for PDT in various tumours.

8427-76, Session 15

Oxygen independent antimicrobial photodynamic therapy using RU based photosensitizers

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Antimicrobial photodynamic therapy (PDT) has shown efficacy towards various bacterial strains for a range of different photosensitizers (PS). However the majority of PSs undergo Type 2 reactions which occur when a PS reacts directly with molecular oxygen to produce singlet oxygen, a highly reactive species and ultimately resulting responsible for eukaryotic and prokaryotic cell death. However, their PDT effectiveness is compromised during the sterilisation of anaerobic bacteria under hypoxic conditions. Tested photosensitizers, known as Mixed Metal Supramolecular Complexes (MMSC) (Theralase Inc.), demonstrate an oxygen independent photodynamic pathway where the production of singlet oxygen is minimal and does not show a significant contribution to prokaryote inactivation. Photodynamic efficiency of MMSC was assessed in Gram positive Listeria monocytogenes, and Gram negative Escherichia Coli, Klepsiella pneumoniae bacteria incubated with MMSC for 30 min and subsequently exposed to 530nm light source for a total radiant exposure of 66 J/cm^2). Cell viability was determined by plating and counting colony forming units (CFU) for each bacterial strain. Results show an inverse relationship between MMSC concentration (50-500µM) and cell viability for all strains, MIC range 100µM to 125µM. Specifically, antibacterial PDT achieved 8 logs of kill for prokaryotes in liquid aliquots, thus demonstrating an effective sterilization method mediated by these MMSC compounds. Comparable results have been achieved for photodynamic decontamination of the same bacterial strains on surfaces. The benefit of using an oxygen independent photodynamic inactivation needs to be demonstrated for these MMSCs in biofilms where PS penetration and destruction of the biofilm matrix are paramount for sterilization and reduction of recolonization by the same prokaryotes.

8427-77, Session 15

The development of skin immersion clearing method for increasing of laser exposure efficiency on subcutaneous objects

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Methods and Materials.

- The using samples - rats skin (back area, without wool, 1.5×1.5 cm2);

- nanocomposite - hematoporphyrin (molar mass is equal 590 g/M); 1 litre enclosed 7 of hematoporphyrin or 11.8´10-6 M or 70´10 17 molecules; nanoparticles concentration - 18´1014 particles in one litre;

Procedure - Injection of nanocomposite was made 1.06.11 at 7pm in subcutaneous tissue, 0,15 mL. Then animal was killed and samples were freezen with temperature 2°C. The investigations were made on the next day.

- concentration of basic suspension was taken as 1 and then sequentially diluted with distilled water up to achievement the following concentrations: 0,25, 0,125, 0,0625;

- Samples were put in Petri dish filled by a clearing agent (CA); clearing agent - Polyethylene glycol (PG) with molecular mass 300 (Aldrich, USA);

- Sampes were leaved on termo-table with constant temperature about 42°C.

CA temperature inside the cuvette - 37°C;

- The spectral investigations of skin sample fluorescence were made by using spectrophotometer USB4000 (Ocean Optics, USA) from epidermis side; the source of the exciting light (300 , 400 nm) - LED phototerapeutic device AFC (Polironic Ltd., RF);

- The fluorescence spectral measurements were made: before the samples putting in cuvettes; after 30 minutes; after 75 minutes; after 2 hours

8428-01, Session 1

Pattern definition by nanoimprint

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Nanoimprint, since its announcement in 1995, has become an interesting technique to define patterns in particular in the sub-micrometer and nanometer range, e.g. for lithography purposes. As a method that works in parallel it represents a low-cost alternative to serial electron beam writing. Two main techniques have developed, the imprint of UV-curable materials (UV nanoimprint lithography, UV-NIL) and the imprint of thermoplastic materials (thermal nanoimprint lithography, T-NIL). In both cases a thin layer of the imprint material on top of a substrate is brought into contact with a template and the template pattern is replicated during the imprint process.

Though nanoimprint generally is a simple technique, successful processing requires an understanding of the basic relationships. Such inherent issues of both techniques, thermal nanoimprint and UV-nanoimprint, will be addressed and discussed. The mechanical nature of the process, due to its pattern size dependence, may result in a non-uniformity of the residual layers or a non-uniformity of the imprint depth, depending on the equipment used. Pattern formation relies on a viscosity of the imprint material that matches the pressure provided by the imprint system, so material choice may be related with the equipment. Due to the fact that imprint is a contact technique the anti-sticking armament of the template is an important issue. Thin layers that remain stable under typical processing conditions are required. Evacuation of the region between substrate and template may assist cavity filling, but may conflict with alignment or material stability.

With the help of imprint examples and simple theoretical conceptions the potential of nanoimprint for pattern definition will be developed, for the use as a lithography technique and for the use as a direct patterning technique for surfaces.

8428-02, Session 1

Nanoimprint lithography for small volume production of nanophotonic LEDs, VCSELs, and thin-film PV

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Substrate Conformal Imprint Lithography (SCIL) combines the low cost, flexibility and robustness of PDMS rubber working stamps, with the resolution and low pattern deformation of small rigid stamps. To obtain nm resolution we developed a new high modulus silicone rubber (X-PDMS) and a fully inorganic cross-linking, silica sol-gel based imprint resist. This material does not suffer from light- and temperature degradation, as is the case with existing organic and hybrid inorganic-organic imprint resists. The X-PDMS is used in a flexible composite stamp to provide in-plane rigidness to avoid pattern deformation, while out-of plane flexibility is maintained. SCIL uses an ambient sequential contact and release method to bring the stamp in conformal contact with a resist coated substrate, which avoids high forces. The room temperature NIL replica patterning forms a silicon-oxide layer in one minute imprint time and allows replication of sub-10 nm features over 150 mm wafers. The silica patterns are a 1-to-1 (inverse) copy of the stamp and an ideal etch mask for subsequent pattern transfer by standard semiconductor reactive ion etching (RIE). Additionally, sol-gel patterns can be used as functional (optical) components as it is non-absorbing, transparent for UV-VIS-IR and does not degrade by heat or light.

We demonstrate the flexibility of SCIL by replicating photonic crystal patterns on extreme high topology substrates, consisting of individual 1x1mm2 power LEDs on a submount, after which the GaN material is RIE etched. We also fabricated large area plasmonic thin-film a-Si:H solar cells which exhibit 9.6% efficiency (AM 1.5), using an only 90 nm thick intrinsic amorphous silicon layer. This is a 29% improved performance compared to conventional random textures. From 2009 on SCIL is successfully applied in the mass production of polarization stabilized vertical cavity surface emitting lasers (VCSELs) emitting at 850 nm. We imprint sub-wavelength gratings on 3” GaAs wafers, which are subsequently etched in the semiconductor. The wafers are further processed into VCSELs using traditional optical lithography. By replacing traditional e-beam patterning by SCIL we improved performance up to 150% and yield as it enables using a smaller grating pitch which reduces optical losses, while lowering cost. Using the silica imprint resist as a functional component we demonstrate the direct replication of an 18-level Fresnel lenses on wafer scale.

Our robust wafer-scale imprint method and novel resist system demonstrates the whole value chain is ready for research, development and (pre)production to start incorporating NIL technology into products.

8428-03, Session 1

UV-based nanoimprint lithography: a method to fabricate single and multilayer negative index materials

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In this paper we show the fabrication of large area single layer as well as multi-layer negative index materials (NIMs) using Nanoimprint Lithography (NIL). One single NIM layer consists of two patterned gold gratings separated by a dielectric layer such that resonances for the electric and magnetic field occur and negative refraction is achieved [1].

Several approaches have been applied to fabricate 3D negative index materials (NIM) for the infrared regime [2], [3] and recently at visible frequencies using focused ion beam cutting [4]. Those approaches are important steps to move toward devices like perfect lenses and cloaking devices [5], [6].

We will present a stacking method based on a NIL process which is a very fast technique to achieve 3D materials. First single layers of NIM structures are fabricated on Si substrate using a two layer lift-off system. Next the single layers are peeled off using a UV-curable hybrid polymer as “glue”. Performing this process several times on top of each other leads to stacked NIM layers. The stacking process can be performed onto quartz, borofloat or also flexible substrates taking only few minutes. This process works for Split Ring Resonators (SRR) [7] as well as for double gold layer structures like Fishnet and Swiss cross patterns [8]. The Fishnet layers have been characterized using transmission and reflection measurements and using ellipsometry under oblique incidence. The retrieved μ and ε indicate negative n around 1.8 µm for the Fishnet samples and 1.4 µm for the Swiss Cross samples. The achieved alignment accuracy for NIL fabricated samples is around 50 nm [7].

We further will show approaches to fabricate NIMs not only in the infrared but also at visible frequency regime. Here we are faced with the following challenges:

(a) The structure dimensions are usually smaller and aspect ratio higher.

(b) Silver instead of gold has to be used, since for NIM response in the visible we need a high conductivity of the metal. The drawback of silver is its degradation. Here we apply an annealing and passivation step to keep the NIMs stable.

(c) In our process the structures are embedded in Ormocomp. To improve the transmission of the stacked material we use an etching step to open up the holes within the fishnet structures.

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[1] Veselago V G, Sov. Phys. Usp. 10, 509, (1968)

[2] J. Valentine et al., nature 07247 (2008)

[3] Debashis Chanda et al., nature nanotechnology 82 (2011)

[4] C. Garcia-Meca et al. Phys. Rev. Lett. 106, 067402 (2011)

[5] D Schurig et al., Science 314, 977 (2006)

[6] Q Wu et al. J. Opt. Soc. Am. A 24, A45 (2007)

[7] I. Bergmair et al., MEE, 87, (5-8), 1008 (2010)

[8] I. Bergmair et al., Nanotechnology, 22, 325301 (2011)

8428-04, Session 1

Tailor-made materials for nanoimprint lithography as enabler for optical applications

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The nanoimprint lithography (NIL) makes confident steps towards industrial mass production. It can be considered as a valuable enabling technique for new concepts and straightforward solutions (e.g. 3-D manufacturing) which cannot be achieved by conventional photolithography techniques. The success of advanced fabrication technologies is strongly depending on the diversified requirements on multi-tasking materials. The new generation of materials does not only possess excellent imprint characteristics, but also precise optical properties for long-term applications. Hybrid polymers of micro resist technology were developed to cover a majority of prerequisites.

High refractive index and low thermo-optical coefficient are important for optics and photonics to perform on the highest level. Up-to-date manufacturing of optical elements is a full-wafer process including full-wafer imprints or step-and-repeat processes. Mechanical properties of the dedicated materials such as shrinkage, retained stress, and hardness/flexibility values play a major role. For example, thermal stability up to 260 - 270 °C with no change of optical properties and transparency is a must to accomplish a full-wafer level manufacturing process by optical industry.

Materials with tailor-made physiochemical properties can serve as enablers for the combination of different generic processes. Providing the suitable molecular weight, a tailored resist can allow the combination of NIL with 3-D grayscale electron-beam lithography (EBL) and thermal reflow. By this way, imprinted large area gratings (e.g. for anti-reflection or wavelength filtering) can be easily fabricated as surface reliefs on the resist. Such sophisticated 3-D structures are needed for example for backlighting devices. Complex 3-D structures are only generated at specific locations by EBL and refined by thermal treatment without effecting the imprinted relief. Once such a structure with a complex 3-D surface relief is created, UV-NIL allows transferring the master pattern into a transparent hybrid polymer working stamp, which is then used for direct replication by thermal or UV-NIL.

8428-05, Session 1

Nanoimprint lithography for optofluidics

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Invited abstract (NaPANIL session): The integration and interplay between optical and fluidic functionalities defines the emerging field of Optofluidics. Microfluidics enables new types of adaptive optics and sensing systems. One the one hand, fluid flow can be applied to control the optical properties of a device. On the other, and compact sensing systems can be obtained by incorporating optical funcitonality to microfluidic devices, e.g. where the microfludic platform is used for fast and precise delivery of a sample to an optical sensing element. The fabrication of optofluidic devices in plastic by NanoImprint Lithography (NIL) and their performance is discussed. Two types of optofludic devices are discussed. (1) On-chip fluidic light sources - optofluidic dye lasers - which can readily be integrated in lab-on-a-chip devices, and (2) Optothermally actuated nanofluidic chips for stretching, manipulating and analysing single DNA molecules.

8428-06, Session 2

Metallic colour filtering arrays manufactured by nanoimprint lithography

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Nanostructured surfaces are widely expected to play a significant role in photonics, especially in wide-spread products like CMOS imaging sensors, solar cells, LED-based lightning and micro displays. Those expectations are related to two kinds of benefits: improvement of the conversion efficiency from photon to electron (solar cells, photo detectors and image sensors) or from electron to photon (lightning, displays); reduction of fabrication cost. Spectral filtering is already used in the visible range in CMOS sensors, where arrays of ~1µm2 red, green, and blue polymer pads are integrated a few microns above the sensors, which requires several photolithographic steps and introduces a significant thickness in the devices with thus several limitations. One solution will be to realize all spectral filters using an in plane patterning of a single layer.

As already shown by several groups, band pass filtering can be thus achieved in thin nanostructured metallic layer with a sub wavelength pattern. In this work the basic structure is a sub wavelength array of sub wavelength cross etched in an aluminum membrane. 3D FDTD (finite -difference time-domain) simulations were performed in the visible range for an aluminum membrane surrounded by air to optimize the nanostructures design to get blue, green and red filtering. To address several issues related to filtering (metal layer thickness w.r.t. color filtering, wavelength dependency, incident angle dependency, polarization behavior), we have studied double-breasted rectangular hole array. Stamps were then manufactured with high resolution ebeam lithography processes with Shape Correction procedure. Imprint and etching processes were then developed to manufactures 864 color filters (100x100 μm^2 each) on 200 mm wafer (figure 3) with processes compatible with IC manufacturing line.

8428-07, Session 2

Functional optical surfaces: challenges for large area nanoimprints and perspectives for applications

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Micro and nanoscale patterns are a promising way to bring new optical functions to every day materials like window glass for buildings or automotive applications. Today nanoimprint is established as a flexible research tool in the area of nano and microoptics. One of the main advantages of nanoimprint is that it is possible duplicate very complex structures at various length scales using rather simple equipment. In

principle the only thing needed is a master stamp, a resists and ability to apply a pressure. However, the use of nanoimprint for industrial products is still in a precursory phase. Depending on the area of application scalability, speed, feature sizes and reliability of the technique can be an obstacle. In the present talk we will present results from our research on nanoimprint for large area optical coatings for housing products obtained within the FP7 network NaPANIL. We will focus on silica sol-gel resists due to their high durability and optical properties and soft stamps in order to be able to contact large areas and stiff substrates. We will through specific examples illustrate key issues for nanoimprint like the master design, the master enlargement, the coupling between the mechanical properties of the mould and the rheology of the resists.

8428-08, Session 2

Swellable hydrogels imprinted for optical sensor structures

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Polymer hydrogels offer strong potential for use in chemical and biological sensors, because of their ability to respond to a small change in their environment with a large physical effect, manifested by an increase in the amount of absorbed water and a related change in volume. Several designs using 2D grating and 3D photonic crystal structures have been demonstrated. Ultraviolet curable hydrogels, based on combinations of PEG, NIPAAm and AA have been developed for the NIL process. The hydrogel being presented is a tert-polymer PEGDMA-NIPAAm-AA: poly(ethylene glycol dimethacrylate-co-N-Isopropylacrylamide-co-acrylic acid). This stimulus-responsive or “intelligent” hydrogel is sensitive to pH and to temperature. It has been modified in order to be UV-nanoimprintable. Viscosity and photosensitivy were adjusted by combining photoinitiators and solvents.

Line grating designs have been fabricated by NIL and used to test the rate of expansion of the imprinted hydrogels as a result of water absorption, and the related change in optical signal, which was measured using a diode laser source (488 nm) from hydrogel imprinted on silicon substrates. NIL enables multiple level structures to be contained in a single stamp and imprinted in hydrogel, and this aspect of the fabrication process is extremely useful for up-scaling to mass-production. Stamp preparation involves a double replication in Ormostamp of a silicon master to obtain a UV-transparent stamp with the correct polarity. In the case of gratings with period 1.5 m and 4.0 m, the total intensity of diffracted light decreases by 46% and 42% respectively after swelling, and the change in the relative diffraction efficiency of the first and second orders, which is not affected by fluctuations in laser power or surface reflectivity, is 33% and 54% respectively. The optical signal is simulated using the rigorous coupled wave analysis, and shows good agreement with measured values, which makes possible the controlled monitoring of changes in the microscale structure via the far-field optical signal.

8428-09, Session 2

NIL for automotive optical components

V. Lambertini, Ctr. Ricerche Fiat S.C.p.A. (Italy)

The automotive industry is one of the largest demanding areas of materials and technologies and it is expected that micro and nanotechnologies will have a large impact on safety, on-board well-being, environment compatibility and fuel saving. The car evolution in the last years is demonstrated by the great increase of electronics installed, which represent today the 15-20% of the overall cost of the car and is expected to grow to 40% in 2015. In the same way, multifunctional surfaces are expected to impact on several interior and exterior components. High brightness lighting systems and displays, antireflective nanostructures, iridescent and self-cleaning surfaces represent examples of functionalities needed to increase comfort and safety of drivers and passengers obtained by nanotexturing of surfaces.

The development of novel industrial nanopatterning methods proposed by the NaPANIL project will speed up the introduction of such a novel concept of human-machine interfaces in the automotive sector; moreover, most of the automotive parts are characterized by 2.5 and 3D curved shapes (as dashboard, cockpit surfaces, interiors trims, windows glasses) which require nanopatterning technologies on curved/non-planar substrates.

Nano Imprinting Lithography (NIL) represents one of the most promising technologies to fabricate these multifunctional surfaces in large volumes at low costs. Recent results obtained in the frame of the EU project NaPANIL show the possibility to fabricate glass and plastic substrates with nanostructured surfaces for different purposes: antireflective properties and transparent electrodes. As demonstration activity within NaPANIL, Centro Ricerche Fiat (CRF) proposed a transparent emissive display to deliver information to the driver in a see-through head-up mode. While in conventional HUDs, which are virtual, the image is projected out of an imaging chain and reflected by a transparent see-through combiner, in the CRF head-up display the emitting layer is integrated into the transparent combiner itself.

8428-10, Session 2

Enhancement of extraction efficiency in nanoimprinted optical device structures

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Improving the luminous efficiency, reducing the production cost and increasing the lifetime of OLEDs are the current key issues to be solved in order to achieve widely commercialized OLEDs. Here we report on a method to enhance the light-emission efficiency of printable thin films of polymer doped with core-shell nanocrystals or dye molecules via metallic nanoparticles and nanoimprinted plasmonic crystals. We experimentally show a strong fluorescence enhancement of emitters by coupling excitons with the localized surface plasmons of metallic nanoparticles and with the surface plasmon polaritons at the periodic metal layer interfaces. By combining the field susceptibility technique with optical Bloch equations, we examine the interaction of the quantum and plasmonic entities at small distances. We show that the nanocomposite polymers present an excellent processability to be patterned by nanoimprint lithography and that emitted light can be efficiently diffracted by nanoimprinted photonic crystals structures. We will then present how nanoimprint lithographic techniques are particularly suited for the realization of ITO-free OLED device structures. We tested them to realize nanopatterned metallic electrodes containing photonic crystals to couple the light out and plasmonic crystals showing extraordinary transmission. At similar current densities, a two-fold electroluminescence is achieved with devices having doubled-sided nanoimprinted metallic electrodes as compared to a control OLED with an ITO anode. The use of combined nanoimprint lithography processes has the potential to expand the performance range of various organic optoelectronic devices. Our results prove the potential of the prepared luminescent functional materials for micro and nano fabrication; suggest the use of nanocomposite materials in prospective nanoplasmonic applications and the use of nanoimprint lithograpy to optimize the geometries of OLEDs cathode and the anode independently in order to enhance their light extraction efficiency.

8428-44, Poster Session

Low f-number microlens array fabricated in thick resist

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In this work, the design and fabrication of a low f-number cylindrical microlens array are presented. The lenses were fabricated on a 12 μm-thick Novolac type photoresist, using a contact printer exposure tool. A photomask with geometry of repetitive 6 μm line and 4 μm open space features was employed for pattern transfer. Due to the relatively thick resist layer, light penetrates the resist film and diffracts underneath the opaque structures of the photomask, generating a microlens structure with parabolic phase profile with f# less than unity. Since the open apertures of the photomask are approximately 10 times the used wavelength, scalar diffraction is suitable to modelling the exposure step. Numerical calculations based on scalar diffraction theory were employed to model the light propagation inside the resist, determining the aerial image as a function of its thickness. Assumptions based on van Cittert-Zernike theorem were also used to assure a partial coherence illumination regime, with a coherent length larger than photomask apertures.
After some empiric combination of exposure doses and developer concentration, a suitable lithography process was established. The resist response characteristics - expressed by its contrast curve, as well as its absorption rate - were used to simulate the photo resist cross section profile obtained after exposure and development steps. These profiles where then compared with SEM images from fabricated microstructures and a good match between numerical and experimental results was found.

8428-45, Poster Session

Fabrication of near- or mid-infrared wire-grid polarizers with WSi wires

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Wire grid polarizers are attracting much attention for their possible application in imaging systems and liquid crystal devices due to their features including compactness, and good polarization efficiency.
In previous work, we verified that tungsten silicide (WSi) has a large extinction coefficient, microfabrication capability, chemical and thermal durability as well as strong adhesiveness to substrate, and that was suitable for a wire material in the mid-infrared range.

In this work, we fabricated a subwavelength-grating structure on the Y_2O_3 ceramic substrate, which has higher transparency than silicon in the mid-infrared range. After coating a photoresist on this substrate, we formed a grating pattern of 350-nm pitch by the two-beam interference of the He-Cd laser (325-nm wavelength). By using this photoresist grating as a mask, WSi was etched with reactive SF_6 ions. The thickness d, the period Λ, and the fill factor f of the wire grid layer were, respectively, d = 250 nm, Λ = 350 nm, and f of approximately 0.5. The transmittance of the transverse magnetic (TM) polarization was greater than 70% in the 3-7-μm wavelength range without antireflection films and the extinction ratio was over 20 dB in the 2.5-5-μm wavelength range. A high extinction ratio of 25 dB was obtained at 3.2-μm wavelength. In addition, we also fabricated a near-infrared wire-grid polarizer consisting of a 230-nm pitch and 110-nm thickness WSi grating on a SiO_2 substrate. The TM polarization transmittance of the fabricated polarizer exceeded 80% in the 1000-1600-nm wavelength range. The extinction ratio was higher than 20 dB in the 650-1500-nm wavelength range.

This experimental result verified that WSi is a suitable wire material for the wire-grid polarizser in the near- and mid-infrared range. If the WSi gratings are formed on both sides of the substrate, the extinction ratios of both elements will be enhanced up to approximately 40 dB. These wire-grid polarizers are expected to extend to various application areas such as optical modulators, optical isolators, ellipsometry, spectroscopy, and security imaging.

8428-46, Poster Session

New industrial and innovative writing machine for the fabrication of sol-gel TiO2 based sub-micrometric period diffraction gratings

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New industrial and innovative writing machine for the fabrication of sol-gel TiO_2 based sub-micrometric period diffraction gratings

Diffraction Gratings are widely used in many areas such as displacement sensors, spectroscopy, white light processing, etc. Their fabrication represents a great challenge in matter of cost, time and technology. Since industry needs to reduce cost and time as much as possible, we seek to improve both by two mean ways. The investigations, made at the Laboratoire des Matériaux et du Génie Physique (LMGP) in Grenoble (France), about photo patternables sol-gel thin films, and direct dynamic writing of diffraction gratings at the Laboratoire Hubert Curien (LaHC) (Saint Etienne, France) led to results presented here. Both areas of investigation are compatible with the process of large surfaces: cheap sol-gel chemistry [1] allows writing any kind of pattern on large TiO_2 xerogel film such as diffraction gratings; write on the fly technology, developed in LaHC[2][3], allows the direct writing of diffraction gratings along large substrates. In partnership with KLOE Company, we successfully transferred “write on the fly” technology (involving grating phase mask, signal processing and nanometric displacement control), from LaHC prototype bench to the laser beam writing industrial machine (KLOE’s Dilase 750). Using this equipment, and the photopatternable xérogel films, we demonstrated the fabrication of long TiO_2 diffraction gratings with sub-micrometric period. We will discuss here parameters and optimizations necessary for the industrial use of this equipment. We will also deal with the potential of such innovative and unique laser beam writing machine, coupled with dynamic lithography using phase mask, enabling cost-effective and rapid grating writing on photopatternable TiO_2 based sol-gel thin film.

[1] S. Briche, Z. Tebby, D. Riassetto, M. Messaoud, E. Gamet, E. Pernot, H. Roussel, O. Dellea, Y. Jourlin, et al., “New insights in photo-patterned sol-gel-derived TiO_2 films,” J Mater Sci 46, 1474-1486 (2010) [doi:10.1007/s10853-010-4949-7].

[2] E. Gamet, Y. Jourlin, S. Pelissier, R. Min, S. Reynaud, C. Veillas, J.-C. Pommier, and O. Parriaux, “Flying phase mask for the printing of long submicron-period stitchingless gratings,” Microelectronic Engineering 83, 734-737 (2006) [doi:10.1016/j.mee.2006.01.002].

[3] P. Müller, Y. Jourlin, C. Veillas, G. Bernaud, Y. Bourgin, S. Tonchev, and O. Dellea, “On-the-fly writing of a long grating phase mask,” Optical Engineering 50, 038001 (2011) [doi:10.1117/1.3549254].

8428-47, Poster Session

Highly efficient relief diffraction gratings inscribed in a chalcogenide bulk glass by a femtosecond laser

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We report on femtosecond laser fabrication of highly efficient relief diffraction gratings in the surface of a chalcogenide bulk glass. The diffraction gratings with d = 3, 7 and 12 um were inscribed in chalcogenide Ge15Ga3Sb12S70 bulk glass by a Ti:saphire laser operating at 800 nm with the repetition rate of 1 kHz and the pulse duration 600 fs. The diffraction efficiency of the prepared gratings was confirmed over 60 % for a 650 nm laser in the first diffraction order and transmission operation.

The fabrication involved local heating of the glass surface in the path of a focused femtosecond laser beam, its melting and evaporation. The energy of the beam increased gradually from 1.5 and 3.0 to achieved 4.5 uJ providing the widths of the incribed channels of about 2, 4 and 6 um with approximately semicircular shape. A sample was placed on stabilized stage with independent moving in all axes controlled by a computer. A beam was aligned by means of a green laser with the same optical path as the fs-laser beam. We used a lens with the magnification of 40× to focus a beam at the surface of glass. The speed of stage moving was set to 150 um/s. Each spot in the beam path received 5 pulses.

We have also inscribed a “composite” diffraction grating (3.0×3.0 mm) composed of all the above mentioned gratings together with mutual tilt of 52 ° (for d = 3 um) and 118 ° (for d = 7 um) related to the orientation of the grating with d = 12 um. Such a grating provides highly effective multi-directional difraction of the light observed at various wavewlenths, 650, 974, 1215 and 1440 nm, respectively.

Fs-laser writing has been already demonstrated as an effective tool for fabrication of under surface “buried” waveguides or diffraction gratings employing large photo-induced changes in the refractive indices of the features inscribed in chalcogenide bulk glass. The femtosecond laser writing represents accurate, contactless, mask- and etching-free micro-processing benefiting from a precise sample-to-beam alignment by computer controlled positioning system. We suppose that the femtosecond laser writing in chalcogenide bulk glass surface would enable the patterning of functional micro optical elements such as “built-in” micro-diffraction gratings on the ends or on the surfaces of multi-mode optical fibers or the ends of buried waveguides.

8428-48, Poster Session

Laser stabilized by acousto-optic cells for optoelectronic oscillators

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In order to improve stability of an opto-electronic oscillator (OEO) based on a MgF2 resonator, it is necessary to stabilize optical frequency of a laser at 1.55 µm. Although Pound-Drever-Hall technique can be used for the purpose, in this research, we investigated application of acousto-optic cells based on a paratellurite TeO2 crystal to stabilize a microwave signal generated by the opto-electronic oscillator (OEO). Bulk acoustic waves at two radio (RF) frequencies near 60 MHz were launched in the two identical cells providing a required locking on of a microwave signal. Quality factor of the optic resonator was of the order 10^8. As a result, difference between the two RF signals could be varied from 0 to 2 MHz. In our case, we sent an extraordinary polarized laser beam on ultrasound at Bragg angle of light incidence corresponding, at the RF frequency 60 MHz, to a deflector regime of the cells operation. It helped to perform a critical alignment of the two cells. To generate RF signals, we had to lock a Voltage Controlled Oscillator (VCO) on a microcontroller following the microwave frequency generated by the OEO.

8428-49, Poster Session

Design of optical interconnets inspired in multi-aperture optics based in compound insect eyes

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The application of optical interconnection to high-speed and large-capacity transmission of information, with the advantage of conveying information at large bandwidths in free space with less crosstalk in comparison with electronics, has served as motivation for the creation of alternative designs of a new generation of optoelectronic devices. We propose here the design of micro-optical devices inspired in the anatomy of multi-aperture compound insect eyes that will transfer the signal as a multichannel point-to-point interconnection. We based our designs in the configuration of the superposition refractive compound eye. We use the Gabor superlens configuration by means of the implementation of microlens arrays. Proposed configuration, design equations, simulations, and optical performance are shown.

8428-50, Poster Session

Design and fabrication of a novel pump having a pulseless steady flow for bio-applications

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Fluid driving devices have been widely used in many applications, such as pumping, circulating, and cooling systems in handling liquid. Their driving conditions are highly depended on the operation purposes. Some of them have to work in high pressure, high flow rate; and do not care about the flow stability. However, a steady flow with low pressure and flow rate is extremely required for a few fluidic driving devices, especially for those cases utilized in bio-applications.

In tradition, cells are cultured in the liquid medium on a culture dish which provides a proper environment. The liquid medium is still and not able to flow, and therefore no flow shear stress can be induced. Unfortunately, the flow shear stress is the main factor to stimulate cells to have some physiological functions. Thus, a three-dimensional circulating perfusion system was created to simulate cells like staying inside the body. This system supplies cells not only nutrition but also a suitable flow shear stress. The pumping performance is the key to make a steady flow possible.

In conventional peristaltic pumps, they directly compress the liquid to drive it out. This compression often causes an unsteady flow which brings the flow shear stress variation markedly. The suddenly change of a large flow shear stress can damage or flush cells to lead to the fail of experiments. Some special pumps employ multiple driving chambers to generate a steady flow without pulses. However, they are expensive and have a large size not easy for miniaturization. A chamber is designed and formed by using micro-channels that consist of two materials having different surface tensions. A large difference between these surface tensions will greatly improve the pumping performance to provide a pulseless steady flow which can drive the liquid without compressing the liquid for being used in bio-applications. This approach is cost-effective and also easy to miniaturize the pump. The related details will be discussed in this paper.

8428-51, Poster Session

Fabrication of 100% fill factor arrays of microlenses from silicon molds

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This paper reports a batch-fabrication technique based on silicon micromachining of moulds to create, after replication, arrays of microlenses characterized by high fill factors. The technique for single microlens generation (compatible with various types of replication or integration so that microlenses made of plastics or glass can be generated) was reported previously and showed its potential in terms of range of shapes and cost. However, because of subtleties of chemical etching, it was barely possible to generate high fill factor matrices. Thus, in this paper, we describe the analysis of the chemical etching process and the corresponding adaptation of the mask design to achieve 100% fill factors arrays of microlenses. Thanks to the generic character of the process, many different footprints can be achieved such as triangles, hexagons or squares, allowing high fill factors.

Different technologies exist to fabricate microlenses, being reflow of photoresist or diamond turning among the most widely used. However, they are generally either restricted to circular footprints or to rather low numerical apertures, leading to limited fill factor in a matrix configuration. In here, master silicon molds are generated by wet etching in a solution of HF/HNO3 in proportion 1:9. Thanks to the isotropic character of the etching process, spherical profile is achieved although the footprint of the lens can be chosen freely. Thus, hexagonal or triangular footprints can allow increasing the matrix density. However, etching rate for non-symmetrical structures appears to be non-uniform due to mass transfer differences, i.e. its rate becomes higher on mask openings sides than on corners. In our method, identification of etching speeds as a function of the footprint, size and location within the apertures has been done, then apertures onto the photomask have been adapted to compensate the gradient of etching speeds so that we fabricated high fill factor matrices of microlenses. For different footprints, 100% fill factor was achieved even with high numerical aperture. Such technique could be interesting for applications requiring, e.g., enhancement of light coupling efficiencies or dense MEMS based imaging systems, such as array type confocal microscopes.

8428-52, Poster Session

Design and fabrication of microwindmill for fluidic media based on SU-8 for using flow-meter

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This paper introduces a method of windmill fabrication using SU-8. This device is in measuring gas flow using rotational speed of the windmill. An experimental setup is arranged to measure the rotational frequency of the windmill as a function of gas flow.

Measurement of flow velocity of liquid and gas in micron- sized systems are of interest in biological experiments. A major point in design of these blades is the aspect ratio and size.

Our method for fabrication of windmill includes several steps. At first, we coated Cu on SiO2 substrates. And then, it was spin-coated by maP-1275 photoresist. Afterwards a blade pattern is created on the polymer using UV-lithography. A part of the copper which has been exposed is removed by etching and a mask is obtained.

Next, A SiO2 substrate is coated by copper and is then spins coated by Su-8 photoresist. We created the pattern on Su-8 by putting the mask on it and then exposing it by UV-light source. We separate the pattern from substrate using an ultrasonic. Finally, the produced blade is coated again by cu.

Several windmills with different sizes and number of blades were made. A windmill with 4 blades and 1.85mm radius with 40um thickness was made as a first sample by this method. A glass pipette with 250um diameter is passed through the center of the blade as a shaft. An experimental set up was used to measure the performance of this system as a gas flowmetrer.

The presented method is a simple UV-lithography to create micro-windmills. The smallest windmill could be made by this method had a blade with 1.4 mm radius and 40 um thickness due to not using any mask aligner. We compared 4-blade and 8-blade windmills in rotational frequency as a function of gas flow. As a result, the sensitivity of windmills increases with the reduction of sizes and increase the number of blades.

8428-53, Poster Session

Design and fabrication of a polymeric nano-precision micro z-stage

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Stages with Nano metric precision is widely used in nanotechnology and nanolithography. This paper explains the fabrication and characterization procedure of an electrostatically actuated polymeric micro stage. In contrast to piezoelectric stages, this micro stage has a comparatively simple and cost effective fabrication procedure. Furthermore, low Young Modulus of polymers made them a suitable basic material in comparison with their traditional counterparts. In this paper, SU-8 photoresist were used as the construction material and the photolithography technique were used to realize the stage.

Our method for fabrication of the stage consists of several lithographic steps. At first, the conductive pads were fabricated on a SiO2 substrate using a positive tone photoresist in the projection lithography setup. After that, the samples were spin coated with the SU-8 polymer. As the SU-8 polymer is a negative tone photoresist it can be used both as a construction material and the mask conveyance medium. Therefore, two consecutive SU-8 spin coating and projection UV-lithographic steps were done on the prepared substrate. Finally, a conductive layer were coated using a PVD coating method and after developing the substrate, the designed construction was realized. The fabricated stage consists of a plate suspended by four L-shape cantilevers. The conductive layer on the top of the plate works as the upper electrode and also as a reflecting component. By applying a dc voltage difference to the upper and lower electrodes, the stage would attract to the substrate and therefore by a precise control on the applied voltage would yield a precise control on the position of the stage.

For the characterization of the device, we put the stage as the movable mirror in a Michelson interferometer setup. The shift in the interferometric patterns reveals the nano-movements of the stage. In conclusion, a fabricated stage with a 1500um by 1500um plate which was suspended 20microns above the lower electrode was made, and exhibits Nanometric movements.

8428-54, Poster Session

Design and numerical simulation of an optofluidic pressure sensor

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We present a numerical design procedure for an all optical compact sensor by means of integrating the optofluidics with polymer interferometers to measure the microfluidic air pressure and flow rate. The design is based on a flexible air gap optical cavity that can generate an interference pattern when illuminated by a monochromatic light. The optical firings pattern directly depends on the pressure. In our numerical simulations, we take the effects fluid flow rate, solid deformation, and the light interference into account. We use the beam propagation method (BPM) for simulating the optics and the finite element method (FEM) for simulating the mechanics. The significant features of the proposed sensor lies with its low power consumption, compactness, low cost, and short length (200 μm). This sensor can operate under pressure range of 0-60±6% psi at constant temperature of 20 C.

8428-56, Poster Session

Application of epitiopropylcarbazole and carbazolylalkylmethacrylate copolymers as holographic and e-beam recording media

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Recently a special attention has been given to the elaboration of the new sensitive media for the holographic and e-beam recording of periodic nanostructures. In this field polymer compositions attract the great interest due to their specific optical properties, low cost and easy fabrications. They can be used for both holographic and e-beam recording of patterns and diffraction grating structures. Variation of polymer composition makes it possible to change their registration properties in a wide range.

In recent works authors investigated holographic recording media on a basis of polyvinylcarbazole (PVC) and polyepoxypropylcarbazole (PEPC), sensitized by derivates of polyhalogen of methane (CHI3, CHBr3, etc.) and have shown that photostructurization of layers from these materials occurs on the cation-radical mechanism. It was revealed that the given materials possess selective solubility that allows receiving relief diffraction images.

A weak particularity of layers on the basis of PVC or PEPC is the fact that at thicknesses more than 1 µm layers are fracturing and stratifying. For improving the quality of recording media copolymers: (i) epitiopropylcarbazole with epoxypropylcarbazole (T-PEPC:PEPC); (ii) carbazolylalkylmethacrylate with octylmethacrylate (CAM:OMA); and (iii) carbazolylethylmethacrylate with methylmethacrylate (CEM:MMA) were synthesized. The layers from these copolymers with thickness of about 1,0 µm were used for holographic and e-beam recording of diffraction gratings with period of 1 µm. Holographic recording was carried out by He-Cd laser (λ=0,42 µm) and e-beam one in scanning electron microscope BS-300.

For holographic recording all synthesized polymers were sensitized with iodoform CHI3. It was determined that to achieve the maximum photosensitivity the optimal concentration of CHI3 in the polymer was about 10 mass%. Irradiation of the T-PEPC:PEPC (1:1) layers by UV-light resulted in appearing of absorption band at 0,65 µm in the visible range. Under the dark storage of the irradiated films the intensity of appeared optical band increased. This post-recording effect yielded the enhancement of absorption diffraction gratings formed by holographic recording in T-PEPC:PEPC layers. After selective etching treatment the diffraction efficiency of gratings recorded in T-PEPC:PEPC reached for the thin films the value about 26% that was approximately 3 times greater than one for gratings formed in the PEPC films.

The holographic gratings were formed in CAM:OMA (60:40 mol.%.) layers as well. Selective etching of holographic recorded gratings led to increasing of diffraction efficiency up to 20%. Also it was shown that additional activation of layers CAM:OMA by chloranyl allows to reach value of photosensitivity of 10-3 cm2/J.

For gratings formed by e-beam recording in CAM:OMA layers the post-recording effect resulted in efficiency increasing. Diffraction efficiency as much as 34 % has been obtained for relief grating formed by chemical etching. The influence of post-effect and storage in the dark on the diffraction efficiency was observed.

Single (N=1) and superimposed crossed (N=2 and N=3) diffraction gratings of 1 µm period were formed on CEM:MMA layers (30:70 mol%) by e-beam recording. Like-oriented superimposed gratings with periods of 0.8 µm and 1 µm were formed as well.

A nontrivial dependence of diffraction efficiency (η1) on beam current (I) has been revealed for single gratings. Namely, a sharp rising of η1 with I followed the exceeding some threshold beam current value Ith. Diffraction efficiency increased approximately by one hundred and without etching achieved value as much as 8÷10%. The SEM study of surface morphology confirmed, that high efficiencies were produced by relief gratings. The threshold character of e-beam recording, yielding the relief gratings of relatively high efficiency, took place not only for fresh layers but also for one aged layers. The value of diffraction efficiency increased up to 30-34% after chemical etching.

Diffraction structures of superimposed gratings produced multi-beam light diffraction. It was revealed that diffraction efficiency of superimposed grating exceeded one of single grating when beam current values were nearby Ith value. This effect was caused by local enhancement of relief at nodes of intersections of grating structure lines due to additional electron irradiation.

Relief grating structures formed by direct e-beam recording exhibited high stability upon both prolonged dark storage and white light illumination.

8428-11, Session 3

Volume multiplexed holographic optical elements for narrow-band optical filtering and beam combining

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Unique properties of volume Bragg gratings (VBGs) enable recording of multiple elements in the same volume of recording material (volume multiplexing). This paper will review recent achievements in multiplexing of high efficiency volume Bragg gratings. VBGs are recorded by holographic techniques in the bulk of photo-thermo-refractive (PTR) glass. Such PTR-glass VBGs can be fabricated with thicknesses of several centimeters and can have tens of thousands of grating planes that enable ultra-narrow band spectral and angular filtering with bandwidths less than 10 GHz and angular selectivity as low as 0.1 mrad. This is orders of magnitude narrower than feasible with equivalent thin film or polymer VBG filters. Multiplexing of several VBGs in one volume has already been shown previously. However, recent advances in VBG technologies make it possible to multiplex in one volume several gratings with relative diffraction efficiency exceeding 99.9% at different wavelengths. For example, we will show measurements performed with multiplexed Raman notch filters at 532 and 633 nm with optical density OD>3 at each wavelength. We will also show other applications of multiplexed VBGs such as, spectral beam combining, coherent beam combining, angular magnification, and others.

8428-12, Session 3

Holographic exposure of subwavelength circular gratings using cones based interferogram

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The growing interest in light beams of circularly symmetrical polarization distribution calls among others for elements diffracting such beam within the same symmetry frame. One of these is a radial (or azimuthal) polarizer with circular lines letting through the local TM (or TE) polarization component of an unpolarized incident beam. Such element is usually fabricated by e-beam lithography which is very costly, and actually not so well adapted since e-beam pattern generators have difficulties to print lines with arbitrary directions off the standard 0, 90 and 45 degrees. An new holographic optical interference scheme has been designed to produce a circular line interferogram from a azimuthally polarized printing beam. It uses transmissive and reflective cones to print circular grating lines in a photoresist layer. The angle of the cones is adapted to cover a restricted period range. The principle of the method will be described and applied to the fabrication of a radial polarizer.

8428-13, Session 3

Optical diffraction into thick slab waveguides: a finite-beam RCWA approach to solve extremely asymmetrical scattering-EAS in slanted holographic gratings

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Extreme Asymmetrical Scattering (EAS), by holographic slanted Bragg gratings of finite thickness embedded in the core of optical waveguides, appeals to right-angle optical coupling and optical interconnects. In EAS the grating is neither transmissive nor reflecting and a resonant configuration is established [1]. Diffraction efficiency η can nevertheless be evaluated, as the ratio of the flux of diffracted power P1 and input power P0, at a suitably defined cross-section along the propagation of diffracted beam. To solve EAS in guided optics a numerical approach is mandatory. Single-mode propagation on micrometric volumes, as in fiber-to-waveguide optical couplers, is treated by numerical methods which are unfit for wide computational domains, as is for thick optical slab waveguides.

We have implemented a Finite-Beam Rigorous Coupled-Wave Approach (FB-RCWA) [2,3] to solve for guided-optics propagation in the presence of holographic gratings and for macroscopic volumes. By FB-RCWA, the spatial evolution of any optical diffraction order can be calculated. Thick waveguides operating in highly multimodal regime can be treated, as well as widely extended illuminated regions up to a few millimeters. No limitation on the depth of grating dielectric modulation is assumed.

We have focused on the propagation of the first-order diffracted field in Bragg condition.

In dependence on the design parameters, a resonant behavior is established for Bragg order propagation along the waveguide and the optimum coupling length Lc is defined. The differences in diffracted field distribution and efficiency, when passing from the few-modes regime to the highly multimodal regime are highlighted. In thick slabs, $\eta > 90\%$ is demonstrated, for input illuminated apertures of length $L \geq Lc$.

The effects of Bragg detuning, leading to departure from resonance, are quantified, both in distribution and amplitude of the diffracted field. The bandwidth in diffraction efficiency, i.e. optical coupling, is evaluated.

1- D. K. Gramotnev, J. Phys. D: Appl., Vol. 30, (1997), 2056.

2- T. A. Nieminen, D. K. Gramotnev, Opt. Commun. Vol. 189, (2001), 175.

3- Jon M. Bendickson, et al. J. Opt. Soc. Am. A, Vol. 18, (2001) 1912.

8428-14, Session 3

Industrial fabrication of an optical security device for document protection using plasmon resonant transmission through a thin corrugated metallic film embedded on a plastic foil

J. Sauvage-Vincent, Hologram Industries (France); Y. Jourlin, S. Tonchev, C. Veillas, P. Claude, O. Parriaux, Lab. Hubert Curien (France)

The resonant transmission due to plasmon through metallic film is well known and understood. The best known and the most popular is the transmission through a metallic film perforated by arrays of slits or holes. Also resonant plasmon transmission through continuous thin corrugated metallic film have been well described and explained in many papers, less known but it seems more applicable for an industrial process.

The authors will present an application of the extraordinary transmission with a continuous metallic layer for the protection of documents. Through a review of the Optical variable component used in the protection of document (as banknote, passport, ID card), and especially those working on the 0th diffracting order, the authors introduce the new plasmonic component as a new class of "see through effect" in the ZOD (Zero Order Device) category. The authors demonstrated the specificity of the plasmonic component using both collinear and conical incidence; to be well recognized by a non advertised people with naked eyes by a very simple checking movement, without any simple or sophisticated tools (polarizers, etc...). The easy to check effect is coupled to a complexity of fabrication, and so very hard to counterfeit. The authors will present how this well known plasmon resonant effect has been transferred into industrial product using roll to roll process on plastic foils.

8428-15, Session 3

Diffraction grating with suppressed zero order fabricated using dielectric forces

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We have demonstrated a new electric-field assisted approach to producing solid optical devices with micrometre-scale features for which the optical properties are voltage pre-selected when the optical medium is in its liquid phase [1]. As an example we have shown how continuous adjustment of the voltage during UV curing of a liquid resin layer (NOA65) can produce a solid grating with the particular tailored optical property that the intensity of the zero transmitted order was suppressed.

A uniform film of liquid UV curable resin was produced as a drying ring from an organic solvent on top of a set of interdigital electrodes. Applying a 10 kHz square wave voltage to each alternate electrode finger creates a static sinusoidal corrugation at the liquid resin-air interface due to dielectrophoresis forces [2]. The device was mounted horizontally and illuminated in transmission with laser light of wavelength 633 nm polarised perpendicular to the corrugation direction. The 1-dimensional periodic change in the thickness of the transparent resin layer creates a 1-dimensional spatially periodic modulation of the optical path, and this acts as a phase grating which diffracts the transmitted laser light for which the amplitude of the grating. Continuous in-situ voltage-controlled adjustment of the modulation amplitude, and thus the optical diffraction pattern, for laser light at 633 nm transmitted through the layer was carried out simultaneously during UV curing to produce the fully cured solid phase grating. A fully cured solid phase grating was produced with the particular voltage-selected tailored optical property that the zero transmitted order was suppressed for laser light at 633 nm.

Our approach suggests a potential manufacturing technique in which an automated optical intensity-voltage feedback control loop can be used to create a device with particular optical properties. Any changes in refractive index, volume (and thus grating shape), surface tension and dielectric constant of the UV curable resin during the curing process would be compensated for. A simple phase diffraction grating has been demonstrated, but the techniques could be extended to more complex diffractive optical elements.

References

[1] G.G. Wells, N. Sampara, E.E. Kriezis, J. Fyson, and C.V. Brown, "Diffraction grating with suppressed zero order fabricated using dielectric forces", Optics Letters, in press (2011).

[2] C.V. Brown, G.G. Wells, M.I. Newton and G. McHale, "Voltage-programmable liquid optical interface", Nature Photonics, 3(7), pp 403-405 July (2009)

8428-16, Session 3

Interferometric inscription of volume Bragg gratings in a commercial high-refractive index glass (S-TIH53) by 400 nm femtosecond (fs) laser pulses

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Volume Bragg gratings (VBGs) in specific glasses offer great potential to integrate a wavelength selective mirror in other transmitting components. Furthermore, VBGs could be used for reduction of bandwidth, beam combination or pulse compression with chirped VBGs in a single element.

In this paper we present investigations on such VBGs which are based on a periodic refractive index modulation. This modulation can be generated by a holographic illumination in photosensitive materials or by high intensity fs laser radiation for materials without classical UV-photosensitivity. Often point-by-point inscription is used to fabricate VBGs by focusing the light tightly into the material and by scanning the whole sample. However, extreme mechanical requirements for positioning and moving of the sample make this technique less applicable. We demonstrate here VBGs inscribed with a non-scanning technique in the commercial glass S-TIH53 from OHARA using a Talbot-interferometer. In this case the sample is located directly in the area of interference. As a laser source we use a frequency-doubled Ti:Sa-amplified laser at a wavelength of 400 nm and with pulses of a length in the order of 300 fs (FWHM). We characterize these gratings by external Bragg reflection measurements. Gratings with a length of about 1mm and a height of 0.1 mm have been realized, which prove for the first time the feasibility of fs laser pulse inscription of VBGs at 400nm wavelength for this type of commercial glass.

8428-17, Session 4

Design and fabrication of advanced fiber alignment structures for field-installable fiber connectors

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Fiber-To-The-Home (FTTH) networks have been adopted as a potential replacement of traditional electrical connections for the ‘last mile’ transmission of information at bandwidths over 1Gbit/sec. However, the success and adoption of optical access networks critically depend on the quality and reliability of connections between optical fibers. In particular a further reduction of insertion loss of field installable connectors must be achieved without a significant increase in component-cost. This requires precise alignment of fibers that can differ in terms of ellipticity, eccentricity or diameter and seems hardly achievable using today’s widespread ferrule-based alignment systems.

Novel low-cost structures for bare fiber alignment with outstanding positioning accuracies are strongly desired as they would allow reducing loss beyond the level achievable with ferrule-bore systems. However, the realization of such alignment system is challenging as it should provide sufficient force to position the fiber with sub-micron accuracy required in positioning the fiber.

In this contribution we propose, design and prototype a bare-fiber alignment system which makes use of deflectable/compressible micro-cantilevers. Such cantilevers behave as springs and provide self-centering functionality to the structure.

Simulations of the mechanical properties of the cantilevers are carried out in order to get an analytical approximation and a mathematical model of the spring constant and stress in the structure. Elastic constants of the order of 1E4 N/m to 1E5 N/m are found out to be compatible with a proof stress of 70MPa. Finally a first self-centering structure is prototyped in PMMA using our Deep Proton Writing technology. The spring constants of the fabricated cantilevers are in the range of 4 to 6E4 N/m and the stress is in the range 10 to 20 MPa. These self-centering structures have the potential to become the basic building blocks for a new generation of field installable connectors.

8428-18, Session 4

Micromanipulators for a flexible automated assembly of micro optics

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Current market developments are pushing towards miniaturization of laser systems and more efficient production technologies for higher output quantities. Both trends call for new and improved solutions for an automated assembly of laser optics, as a large share of manufacturing cost are caused in assembly. In this presentation the specific challenges in laser assembly will be derived from the analysis of resonator mirror and collimation lens alignment tasks. An appropriate concept for flexible automation in precision assembly of micro optics is presented. The pursued approach is based on a concept for micro assembly with large workspace positioning units (robots, Cartesian systems) which themselves have an insufficient precision for the alignment processes. For fine movements, the robot is equipped with a modular micromanipulator, in this case especially designed for the alignment of micro optical components in laser systems. This results in a very flexible precision assembly system with shortened tolerance chains, compared to classical high-accuracy Cartesian setups with precision axes. The authors will present the realization of the concept in a prototype assembly cell for the assmebly of optical components. The core component of this concept is a compact micromanipulator with six degrees of freedom (DoF) and highest motion resolution which will be described in detail. This covers insights into the design and optimization procedure of the parallel kinematical structure of the manipulator. To maximize the accuracy of the alignment module a continuous monolithic construction has been realized by designing all joints as flexures to eliminate the presence of friction, wear and clearances. The flexure are designed for large deformations to achieve a far-reaching miniaturization of the systems. The dimensioning and optimzation of the flexures will also be presented. The automation concept and the compliant manipulator have successfully been applied for the automated alignment of resonator mirrors in a miniaturized laser system and of fast-axis collimation lenses in front of diode laser bars. Both processes and previous results will be presented as well as new applications in the assembly of VECSEL.

8428-19, Session 4

Single-step laser fabrication and integrated packaging of complex shaped microoptical components

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Well established conventional lithographic techniques, as known from semiconductor industry, are capable of producing planar or 2.5 dimension microoptical elements. However, there exists a growing demand of real 3D compact sized, complex shaped, hybrid, and integrated microoptical components. Nowadays, such elements are usually fabricated in complex, time consuming, and cost-intensive multistep procedures. The femtosecond laser direct writing approach offers unique possibilities to fabricate three dimensional micro/nanostructures in a single step with resolutions beyond the diffraction limit. Recently, several groups have demonstrated fabrication of aspherical and Fresnel lenses, as well as arrays of them from commercially available photoresists synthesized for conventional lithography techniques. However, these materials suffer from shrinkage, mechanical stability, low optical damage threshold, and the lack in the possibility to tune the optical refractive index. In this report, we present single step fabrication of complex shaped hybrid refractive/diffractive microoptical elements, consisting of hemispherical cap microlenses with the diameter ranging from 10 to 100 μm combined with 1D, 2D, or circular transmission gratings with the line widths of 400 nm and grating period of 2 μm. Additionally, conical microlenses with various apex angles (80°, 120° and 140°) were produced. For the direct polymerization a femtosecond laser (300 fs, 200 kHz, 515 nm) was employed. We found out that the intensity of the laser beam required for the repeatable structuring of the microoptics components is 0.5 TW/cm2 and the fabrication time of one element takes 3 minutes with the translation velocity of 100 μm/s. The used novel hybrid organic-inorganic materials contained zirconium or germanium isopropoxides, their refractive index could be tuned by varying the material's inorganic content (from 1.47 to 1.56). The high transparence within the range 400 - 2000 nm was observed.. Optical properties of the microoptical components were measured using custom built setup consisting of He-Ne laser or white light source, microscope elements fixed on the micrometer step motor stage and CCD camera. The measured focal length and focused beam spot size of the hybrid microoptical components were from 20 μm to 200 μm and up to 1 μm, respectively. Imaging properties of the microoptical elements were measured using the metal mask with the letters "VU LRC". We observed up to 3rd order diffraction maxima with clearly resolvable spectral light distribution of the hybrid microoptical elements.. Furthermore, the optical resistance performance was investigated as well. The obtained results of above mentioned polymeric materials exhibit sufficiently high laser-induced damage threshold values which are close to those observed in conventional optical glasses when irradiating with nanosecond pulses at 532 nm. Light loss and signal-to-noise ratio are reduced by incorporating closely packed hexagonal conical lens array. The geometrical shape (RMS=2.5 %) and surface roughness (RMS up to 3.5 nm) of microoptical elements are estimated by optical and scanning electron microscopy, optical profilometry, atomic force microscopy, and x-ray tomography. The obtained experimental results are supported by finite-difference time-domain simulations, allowing optimization of microoptical elements. Applications of the produced microoptical components are demonstrated for light guiding, trapping of microparticles, laser microfabrication, and enhanced microscopy techniques.

8428-20, Session 4

Micro-optical foundry: 3D lithography by freezing liquid instabilities at nanoscale

P. Ferraro, Istituto Nazionale di Ottica (Italy)

No abstract available.

8428-21, Session 5

Miniature wafer-level optical imaging and sensing modules

M. Rossi, Heptagon (Switzerland)

Wafer-level optics fabrication technologies have been successfully industrialized several years ago. Several 100 Millions of optical components have been delivered into mobile phones and smart phones. The latest technology developments have been addressing more complex camera geometries (such as array cameras), novel functions (such as LED beam shaping and light guiding) and a higher level of integration (modules instead of components). This enables new products with so far not possible levels of performance and miniaturization. We are presenting the key features of the new technical solutions and their realization in products like computational cameras and various optical sensors in smart phones and other high-volume applications.

Array cameras require very small lens pitches and efficient means for stray light control. The key developments that enable computational cameras will be presented. Similar developments in wafer-level optics manufacturing technology were required for other types of miniature optical modules. Design studies and results for integrated LED flash modules and typical smart phone optical sensing modules will be presented.

8428-22, Session 5

Polymer tunable microlens arrays suitable for VCSEL beam control

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We report on a simple method for the collective fabrication of polymer tunable microlens arrays suitable for VCSEL active beam shaping. Its principle is based on a SU-8 suspended membrane, surmounted by a polymer microlens, and thermally actuated to achieve a vertical displacement of lens plane. SU-8 resist presents many advantages for MOEMS fabrication, as this resist allows for high aspect ratio patterns and high transparency. In addition, it exhibits a thermal expansion coefficient suitable for thermal actuation. Moreover, this kind of polymer MOEMS can be fabricated on VCSEL arrays with footprints as low as 500μm² enabling a rapid, low cost and wafer-scale integration technology.

We have successfully fabricated this MOEMS on a glass substrate by means of a SU-8 double exposure method and we report on a vertical displacement of ~3μm under an applied power of 27mW (5V). A good agreement with the theoretical thermo-mechanical behaviour is found. Moreover, optical measurements of microlens focus displacement under actuation are presented. We evaluate analytically the focus properties of the system under coherent laser illumination, using the classical ABCD matrix formalism of Gaussian transformation optics. The same approach enables one to assess its tolerance to opto-geometrical parameters, such as refractive index or dioptre curvature.

As a wide range of initial gaps between the membrane and the substrate can be chosen, this MOEMS technology opens new insights for dynamic control of VCSEL beam or for tunable VCSELs fabrication.

8428-23, Session 5

Fabrication of optical microlenses by a new inkjet printing technique based on pyro-electro-hydro-dynamic (PEHD) effect

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Refractive microlenses are acquiring a key role in several applications such as communications, display systems, imaging sensors, photodetectors. Among different methods for manufacturing these optical components, the printing technologies, also thanks to the development of optical grade polymers with suitable thermal and mechanical properties, were advised as direct methods for the fabrication of high-quality and high-precision microlenses overcoming the drawbacks of the traditional techniques which usually require multiple complex processing steps making the fabrication time-consuming and costly.

Recently, an innovative application of inkjet printing technology based on pyro-electro-hydro-dynamic (PEHD) process was used for dispensing droplets of liquid. Basically an appropriate polar dielectric crystal (z-cut lithium niobate, $LiNbO_3$, 500 μm thick) is used for generating pyroelectric charges able to create an electric field which interacts with the liquid reservoir, similarly to what happens in traditional EHD manipulation of liquids.

In the present work, we manufactured microlenses by PEHD effect printing PMMA solutions prepared by employing different solvents

(toluene TOL, N-Methyl-2-pyrrolidone NMP) and their mixtures on glass substrates covered by a transparent tetraethylorthosilicate/1H,1H,2H, 2H-Perfluorodecyltriethoxysilane (TEOS/PFTEOS) film. The hydrophobic surface of TEOS/PFTEOS buffer layer allowed to freeze the drop on the substrate so minimizing the spreading.The effect of the solvent volume mixing ratios on the profile of the microstructures was investigated.

The polymeric microstructures fabricated by using the innovative pyro- inkjet printing technique were analyzed by means of a surface profilometer (KLA Tencor P-10 Surface Profiler) and the geometrical parameters were determined. Through the profilometric analysis we demonstrated that the choice of the solvent or solvent mixture to prepare the PMMA based ink allows to control the microstructure profile. Specifically, we investigated how the chemico-physical parameters of the ink, such as boiling point and surface tension, affect the structure shape modifying the focal length properties

8428-24, Session 5

Fabrication and testing of polymeric microaxicons

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Since their invention, axicon lenses have been of great interest because of their particular optical properties. In fact, they can change an incident Gaussian beam into a Bessel one, which exhibits little or no diffraction over a limited distance and a transverse ring-like shape, and so can be used in many optical applications. For example Bessel beams are extremely useful for optical tweezing as, instead of a single focus point, they present a “focus line”, that is a focus extended for a certain distance (the depth of focus).

To characterize these structures is therefore very important for deducing optical parameters such as the depth of focus or the dimensions of the Bessel rings. Our characterization method is based on digital holography (DH), an interferometric technique which has proved to be very powerful to study and characterize different structures such as MEMS, microlenses, biological samples, etc. In fact, it allows to numerically reconstruct both intensity and phase of the wavefront exiting from the axicon.

In this work DH is used in order to characterize the optical properties of polydimethylsiloxane (PDMS) axicons with different dimensions. They have been fabricated in our labs by an innovative technique exploiting the pyro-electro-hydro-dynamic (PEHD) instability of the polymeric film.

We have fabricated axicons generating Bessel beams with depth of focus of hundred of microns, more than 100 times longer than Gaussian beams of the same dimensions (i.e. waist) would have. This is a clear advantage of axicons for trapping applications in comparison, for example, with the use of a 100x microscope objective. As demonstration, an application in trapping of micrometric objects, using the core of the Bessel beam as optical tweezer, is also provided.

8428-25, Session 5

Large diameter multilevel graded nanostructured microlens

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Recently we have introduced a technology to fabricate 2D gradient index lenses with internal nanostructures and a very high gradient of refractive index. These lenses were fabricated using a modified ‘stack and draw’ technique, commonly used for photonic crystal fiber drawing. With this method, extremely large gradients of refractive index can be attained (> $\Delta n=0.2$ per 5 µm). In addition, we have demonstrated that arbitrary shaping of the refractive index distribution is possible using this technique. The design algorithm, which is driven by the Maxwell-Garnet formula, calculates the effective refractive index of a certain point by averaging the refractive indices in the neighbourhood of this point. The rod distribution is optimised by means of a simulated annealing algorithm using a cost function which measures the difference between the target refractive index distribution and the current distribution of the effective refractive index.

In this paper we report on the fabrication, optical properties and imaging capabilities of nanostructured gradient index microlenses with diffraction limited performance and good chromatic behaviour. We introduce a new fabrication concept for the development of large diameter nanostructured gradient index microlenses based on quantised gradient index profiles and the use of nanostructured meta-rods. We show the dependence of the quality of performance on the number of refractive index levels and the overall lens diameter. The practical limit of the proposed method for fabricating nanostructured GRIN microlenses is determined to be 120µm for 7 discrete levels of nanostructured meta-rod refractive index. The fabricated microlenses show good achromatic behaviour - the observed working distances for illumination at wavelengths of 633 nm and 850 nm are 43µm and 40µm, respectively, while the focal spot sizes remain the same for both wavelengths (within measurement error).

8428-26, Session 6

Customised birefringence in nanostructured micro-optical devices

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The advent of the nanostructuring technology based on the stack and draw method allows the creation of highly customised micro-optical elements with capabilities exceeding those of micro-optical devices fabricated using planar fabrication technologies. In this paper we present the latest results in the design, fabrication and experimental verification of the customised birefringent material fabricated from a periodic one dimensional refractive index variation parallel to the light propagation direction. The stack and draw technology, which is used extensively in the fabrication of photonic crystal fibres, allows the creation of arbitrary refractive index variations by starting from a macroscopic preform (with two or more types of glass rod of ~1-2mm diameter and similar thermal and mechanical properties) and performing a series of draw-down and restacking operations until the final rod diameter is considerably below the wavelength of incident light. The customised birefringent material is composed of the simplest possible refractive index variation - a one dimensional variation with a periodicity of < lambda/2. Initial trials with glass slabs revealed a number of fabrication issues (in particular the propagation of micro-cracks within the birefringent structure) and hence, for the proof of concept devices, square section glass rods were used to create the initial preform. Extensive FDTD modelling of the birefringent structures has shown that the final devices are capable of providing a constant phase shift between TE and TM polarised light over several hundred nanometres. We will present the experimental verification of this modelling work for fabricated devices operating at telecommunication wavelengths. In addition, the finite thickness and mechanical and thermal uniformity of the birefringent material - a zero-order quarter-wave plate having a thickness of between 50 and 200 micrometres - hints at a potential application of the fabricated devices within a high accuracy fibre sensor system.

8428-27, Session 6

Micromachining of optical fibers using selective etching of doped silica glass

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Photonic micro-devices have been extensively introduced over a broad span of applications, ranging from fiber-optic telecommunication devices to biomedical sensors. Integrating such devices with optical fibers can provide many new functions and practical advantages. The current processes for photonic micro-device fabrication and integration with optical fibers are limited in terms of achievable device functions, size, complexity and cost-effective manufacturability. The direct formation of optical devices at the tip, along, or within optical fibers could eliminate these limitations. However, the existing micromachining technologies such as, for example, the lithography based process or direct laser micromachining, exhibit limited compatibility with optical fibers. We present a maskless micromachining process that can effectively reform or reshape a section of an optical fiber into a complex 3D photonic microstructure. This proposed micromachining process is based on the etching rate control achieved by the introduction of dopants, into silica glass through the standard fiber manufacturing technology. Doping with appropriate dopants and dopant concentrations can be used to create highly-preferential etchable areas within a fiber cross-section that can be selectively removed upon exposing the fiber to the etching medium. The doped areas in the fiber cross-section can thus serve as sacrificial layers, similar to those in the case of silicon MEMS production. This requires the design and production of purposely doped structure-forming fibers that preferentially etch into target photonic micro structures. Thus, the shaping of fiber devices can be achieved through the design and fabrication of structure-forming fibers. Detailed analysis of several dopant's impact on the etching rate will be presented. The most promising standard dopant proves to be phosphorus pentoxide (P_2O_5). Doping of the silica with P_2O_5 can yield in glass that etched up to 100 times faster than pure silica, which allows for formation of highly effective sacrificial regions within fiber cross-section. Several all-fiber micro-machined devices including sensors, microcells and micro-resonators were designed and produced using proposed micromachining approach. The proposed method has also a good high volume production potential.

8428-28, Session 6

The micro-optical elements and optical materials of certain spider webs

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Certain spider webs are composed of several types of micro-optical elements made from transparent optical materials. The silks (radial and capture) are almost exclusively protein. The nearly cylindrical silks have diameters in the range 0.1 to several microns and cross-sectional morphology, as studied by transmission electron microscopy, which is cylindrical-multi-layered. The capture threads are coated with aqueous adhesive that also forms into nearly elliptical micro-lenses (adhesive droplets) mounted on the near cylindrical silks. The droplets have minor and major axes of 5-15 microns and 10-20 microns, respectively. The size range reflects different spider species in several genera of the family Araneidae. The adhesive droplets are spaced relatively uniformly along the capture silks. We hypothesise that the layered structure may impart anti-reflection properties, especially in the capture threads and for UV wavelengths, but not enough is known about the optical properties of the aqueous layer, and the skin/glycoprotein layers of the silks to test this hypothesis as yet. The remaining elements of the web are the epoxy junctions tying the radial and the capture threads of the web together. These are irregularly shaped platelets. Progress to date on our research characterizing the optical properties and function of these transparent orb webs has been to interpret the reflection and transmission properties of the elements of the web, and the web as a whole, in natural lighting [1]; to evaluate the optical finish of the surface of the silks and capture droplets [2, 3]; and to measure the principal refractive indices of radial silks using new immersion based methods developed for application to micro-sized, curved optical elements [4, 5]. In this presentation we report on the effect of chemical treatment of transparent spider silks on the principal refractive indices, birefringence, dispersion and morphology of radial spider silks. The latter is characterised by laser light scattering and TEM. Insight into the physical origin of the refractive index properties gained from these measurements will be discussed.

References

[1] D. M. Kane, G. R. Staib, N. Naidoo, D. J. Little and M. E. Herberstein, "The optics of spider orb webs", Proc. SPIE, 2011, 7975, 79750G doi:10.1117/12.880665.

[2] D. M. Kane, A. M. Joyce, G. R. Staib and M. E. Herberstein, Bioinspir. Biomim. 2010, 5, 036004.

[3] D. M. Kane, N. Naidoo and G. R. Staib, J. Appl. Phys. 2010, 108, 073509.

[4] D. J. Little and D. M. Kane, Optics Express 19, No. 20, 19184 (2011.

[5] D. J. Little and D. M. Kane, Optics Letters 36, No. 20, pp.4098-4100 (2011).

8428-29, Session 6

Focused ion beam sectioning of miro-optics as a tool for destructive testing for optical material imperfections

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In prior research we introduced focused-ion-beam (FIB) sectioning, followed by secondary ion (SI) and secondary electron (SE) imaging, as a method for testing the internal material homogeneity of silica and chalcogenide glass microspheres. The technique is readily applied to micro-optics with dimensions of a few microns. The use of both SI and SE imaging of the sequentially sectioned samples was shown to allow accurate assignment of all of the materials in the sample preparation so that inhomogeneities, voids and other imperfections in the glass can be unambiguously assigned as being within the footprint of the micro-optic, and also can be conclusively differentiated from known artefacts of the FIB milling and SI & SE imaging process, for an insulating sample. However, on larger micro-optics, which have relevant dimensions of a few tens, to of order 100 microns, FIB sectioning can become prohibitively time intensive and can require the use of too much platinum in sample preparation. (Platinum is used to manage charging of a dielectric sample and to facilitate high resolution imaging). We now report that improved sample preparation and image analysis has enabled high magnification and high sensitivity study of the glass near the surface of chalcogenide microspheres with diameter of order 70 microns. The chalcogenide glass is Ga_2S_3/La_2S_3, in a 70/30 weight percent ternary (GLS). Clear evidence of an altered, porous layer with a width of the order of 0.1 microns at and near the surface was found. The chalcogenide microspheres had been kept in air, in normal laboratory conditions, for about two years prior to testing. They would normally be stored in a solvent such as isopropyl alcohol. The corrosion at the surface that has been identified indicates that more attention may need to be given to handling and storage of such micro-optics. The FIB/SE-&-SI-imaging technique as a tool for characterizing the homogeneity of glass in micro-volumes is qualitative at this stage. Further research is required to investigate the potential for quantitative analysis.

8428-30, Session 6

Scalar diffraction theory for azimuthally structured fresnel zone plate

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Azimuthally structured Fresnel zone plates (FZP) have been suggested

recently for EUV and X-ray imaging. A conventional Fresnel zone plate (aFZP) consists of a concentric ring pattern where the transmission alternates between zero and one. In an azimuthally structured Fresnel zone plate, the light transmission of the transparent zones is also modulated in the azimuthal direction. The resulting structure is of interest because of its improved mechanical stability as compared to the simple ring structure of an FZP. In that regard, the aFZP is comparable to the photon sieve (PS). Here, we present an analytic model for calculating the optical performance of the aFZP. It is based on scalar diffraction theory. In order to limit the time required for the calculation, it is necessary to introduce a few important simplifications. We show that these do not affect significantly the precision of the calculation. Here, we present the algorithm, show the results of the simulations and compare the aFZP in its performance to the conventional FZP and the PS.

8428-31, Session 7

Diffractive optical combiner for compact see through near to eye display.

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Near to eye display (NTE) are one of the key technologies that can change profoundly handheld devices such as smart phones and tablets. Such a device is often also called Head Mounted Display (HMD). There are many NTE display systems available today, mainly based on LCOS micro displays. However, the real challenge resides on producing a compact light weighted see through NTE, for applications in augmented reality, much similar to the Head Up Displays (HUDs) used in the transportation industry.

One of the key issues for see through displays (as well as for HUDs) is the design and production of the optical combiner. Traditionally, planar and curved dichroics, reflection and transmission holograms using the Bragg selectivity, and more classical conjugate refractive lenses have been used to produce combiners which include also optical functionality (such as an off-axis lens). More recently, waveguide devices based on TIR prism arrays and tilted grating waveguides have been used to produce optical combiners, sometimes also linked to exit pupil expander (EPEs) functionality.

Even though these technologies might be suitable for HUDs, most of them lack the more drastic requirements linked to NTEs. Refractive conjugate lenses are too heavy, curved dichroics too cumbersome, analog holograms too expensive and too sensitive to environment, TIR prisms to heavy and waveguide gratings with tilted sub-wavelength structures too complicated to produce.

We propose a novel technique which uses planar diffractive optics to produce a planar mass replicable optical combiner. We describe its performances as well as its unique fabrication technique. A demonstrator is also presented.

8428-32, Session 7

Microstructured head-up display screen for automotive applications

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A novel see-through screen is developed for automobiles which reduces the size of the head-up display (HUD) unit considerably. Screen size is 10x20cm and it is placed between the windshield and the dashboard. The screen is illuminated by a laser scanning pico-projector and a real image is formed on the screen. The screen has thousands of hexagonal-packed microlenses that are partially reflective and embedded in an index matched medium which provides very good see-through capability. Light reflected from the microlenses expand and form a hexagonal shaped eyebox. The size of the eyebox is 85cm at the horizontal cross-section to provide the driver a comfortable viewing zone while diffusing the light in a controlled manner to achieve the desired brightness. This system is called a direct projection HUD system as the pico projector forms a real image on the screen, which requires the driver to change his/her focus in order to see the road or the content on the windscreen. The system is very compact and does not require any space under the dashboard components, which saves on the precious space for car manufacturers. The screen is manufactured and tested in a real car and performs very well. The design methodology and a video of the HUD operation will be presented at the conference.

8428-33, Session 7

Single-shot capable fast FTIR based on microfabricated 3D multimirror array

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Fourier transform interferometers (FTIRs) are the uncontested workhorses for spectroscopy from the visible to the far infrared, in particular, in the fingerprint range of molecules (400-4000 cm-1). There are widespread applications to chemical and biological analysis and engineering, forensics and homeland security [1], low-energy electron excitations in condensed matter, and metamaterials [2,3]. Commonly, FTIRs such as the widely used Michelson interferometer utilize scanning mirrors to acquire the interferogram. Thus, their capability of measuring fast transient signals is seriously limited.

We solve the problem by recording the interferogram at one instant of time parallel in space instead of taking the data serially in time as it is imposed by the mechanical movement of the scanning mirror. An array of N M binary grating cells of varying grating depth d is set up [4,5]. Each cell features two parallel mirror planes with a mutual distance d representing one discrete position of the scanning mirror of a Michelson. The two mirror planes of each cell intercept half of the incident beam, thus acting as a wavefront-dividing beam splitter that is spectrally neutral. The device could also be described as a lamellar grating with groove depths varying along and across lamellae. It is manufactured as a 3D freespace microoptical component with N M+1 different levels using grey-level deep X-ray lithography as part of the novel multiple moving mask process [6]. So far we achieved 640 individual grating cells ranging from 0 to about 500 µm depths. For high-volume production, plastic moulding can be envisaged according to the well-known LIGA process. Surface roughness, slope and figure error of such mirror surfaces are of good optical quality. The complete spectrometer system includes a pixellated infrared array detector (focal plane array FPA) and a Czerny-Turner-like optical mount [5]. Latest results on spectral quality and transient signals will be presented.

[1] A. Banas, K. Banas, M. Bahou, H.O. Moser, Li Wen, Ping Yang, Z.J. Li, M. Cholewa, S.K. Lim, Detection of traces of explosives after low- and high-order blasts of C-4, PETN and TNT by means of Fourier Transform Infrared spectroscopy, Vibrational Spectroscopy 51, 168-176(2009)

[2] H.O. Moser, B.D.F. Casse, O. Wilhelmi, B.T. Saw, Terahertz Response of a Microfabricated Rod-Split-Ring-Resonator Electromagnetic Metamaterial, Phys. Rev. Lett. 94, 063901(2005)

[3] H.O. Moser, L.K. Jian, H.S. Chen, M. Bahou, S.M.P. Kalaiselvi, S. Virasawmy, S.M. Maniam, X.X. Cheng, S.P. Heussler, Shahrain bin Mahmood, B.-I. Wu, All-metal self-supported THz metamaterial - the meta-foil, Opt. Express 17, 23914-23919 (2009)

[4] H.O. Moser, K.D. Möller, Gitterstruktur und deren Verwendung, European patent EP 0 765 488 B1, June 18, 1994; Grating structure having a plurality of binary lamellar gratings, US Patent 5828492, Oct. 30, 1996.

[5] S.P. Heussler, H.O. Moser, S.M.P. Kalaiselvi, C.G. Quan, C.J. Tay, Multichannel Fourier transform interferometry for fast signals, Opt. Express 19, 12628-12633(2011)

[6] S.P. Heussler, H.O. Moser, 3D micro/nanomanufacturing of arbitrary multilevel plane surfaces, US Provisional Application 61/407502, Oct. 28, 2010; Lithography method and apparatus, US PCT application, Oct. 28, 2011

SPIE Photonics Europe

8428-34, Session 8

Photonically enhanced polymer labs-on-a-chip

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No abstract available

8428-35, Session 8

3D tracking and phase-contrast imaging by twin-beams digital holographic microscope in microfluidics

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A compact twin-beam interferometer that can be adopted as a flexible diagnostic tool in microfluidic platforms is presented. The devise has two functionalities, as explained in the follow, and can be easily integrated in microfluidic chip. The configuration allows 3D tracking of micro-particles and, at same time, furnishes Quantitative Phase-Contrast maps of tracked micro-objects by interference microscopy. Experimental demonstration of its effectiveness and compatibility with biological field is given on for in vitro cells in microfluidic environment.

Nowadays, several microfluidic configuration exist and many of them are commercially available, their development is due to the possibility for manipulating droplets, handling micro and nano-objects, visualize and quantify processes occurring in small volumes and, clearly, for direct applications on lab-on-a chip devices.

In microfluidic research field, optical/photonics approaches are the more suitable ones because they have various advantages as to be non-contact, full-field, non-invasive and can be packaged thanks to the development of integrable optics. Moreover, phase contrast approaches, adapted to a lab-on-a-chip configurations, give the possibility to get quantitative information with remarkable lateral and vertical resolution directly in situ without the need to dye and/or kill cells. Furthermore, numerical techniques for tracking of micro-objects needs to be developed for measuring velocity fields, trajectories patterns, motility of cancer cell and so on.

Here, we present a compact holographic microscope that can ensure, by the same configuration and simultaneously, accurate 3D tracking and quantitative phase-contrast analysis. The system, simple and solid, is based on twin laser beams coming from a single laser source. Through a easy conceptual design, we show how these two different functionalities can be accomplished by the same optical setup. The working principle, the optical setup and the mathematical modeling for 3D tracking is described. Finally, the experimental proof is presented and discussed for in vitro cells in microfluidic chamber.

8428-36, Session 8

Optically mediated dielectrophoretic trapping by electric field gradients in lithium niobate

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In the highly pursued field of micromanipulation, several techniques have been investigated to handle matter on the microscale; each with its benefits and disadvantages. Dielectrophoretic (DEP) forces, for example, are capable of manipulation several thousand particles simultaneously. DEP uses highly inhomogeneous electric field to exert forces on polarizable particles, typically by means of microfabricated electrodes. To overcome the problem of fixed geometries and increase the flexibility of this approach, all-optical creation of virtual electrodes in a photosensitive layer has been introduced as a novel tool for high-throughput particle manipulation [1]. A sandwich structure of a photoconductive layer between two indium tin oxide (ITO) electrodes has been demonstrated to be able to trap 15.000 microbeads simultaneouslyIn our approach, we extend this approach to adaptive and tunable dielectrophoretic trapping by exploiting the bulk photovoltaic effect. This method allows generating the high electric field gradients, which are necessary for the dielectrophoretic trapping. Among the suitable materials, lithium niobate is best characterized, and has the advantage that strong internal fields are generated without the application of an external field. Furthermore, through its electro-optic properties, internal electric fields directly modify the refractive index of the material. In our contribution, we present an in-depth investigation of the two-dimensional internal electric field formation in this material. Digital holographic methods are used to measure the phase shifts inside the material [2], which allow the quantitative calculation of electric fields and the respective gradients. The use of an amplitude spatial light modulator enables us to investigate different two-dimensional trapping scenarios. Time-resolved measurements enable the determination of the material's time constant and maximum electric field, respectively. With this knowledge at hand, the photoconductive sample is integrated in a commercial microscope. This setup permits that lithium niobate samples are structured in-situ and used for dielectrophoretic trapping experiments on the surface of the crystal which can be observed at the same time. Due to the fact that the active surface of the crystal remains accessible, it is easily integrated into microfluidic components [3].

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[1] Chiou et al., Massively parallel manipulation of single cells and microparticles using optical images , nature, Vol. 436, 370-372 (2005)

[2] Ikeda et al., Hilbert phase microscopy for investigating fast dynamics in transparent systems, optics letters, Vo. 30 No 10, 1165-1167 (2005)

[3] Esseling et al., Two-dimensional dielectrophoretic particle trapping in a hybrid crystal/PDMS-system, Optics Express, Vol. 18, Issue 16, pp. 17404-17411 (2010)

8428-37, Session 8

Microoptical device for efficient read-out of active WGM resonators

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Whispering-gallery mode (WGM) resonators are known to offer outstanding properties for applications in photonics and telecommunication. Despite their promising performance as sensors or filters, one major obstacle for the use of WGM resonators in industrial products is their need of expensive components and high-precision setups for their operation, requiring a controlled lab environment. For industrial applications more simple and robust realizations are desired.

Active WGM resonators utilize an optical gain medium for light amplification within the resonator and may be operated as lasers. They offer several advantages over their passive counterparts, such as cheap pump sources and free space excitation of the resonator modes. However, collection of the light emitted from the resonator still bears several challenges. Emission occurs in plane of the resonator and radiation is emitted isotropic along its circumference. Thus, detectors positioned in plane of the resonator may collect only a limited angular segment of the resonator's light emission.

We report on a microoptic device that redirects all in-plane emission of active WGM resonators into a defined off-plane direction. The redirected light can easily be collected using a standard detector. Contrary to other approaches which use asymmetric cavities to achieve directional emission, our microoptical device does not decrease the Q-factor of the resonator.

The microoptic device has an angled profile with an optically smooth surface. Parallel fabrication of several structures is achieved by

replication via hot embossing into a Cyclo-olefin Copolymer (COC) sheet. For enhanced reflectivity the surface of the structured devices is metallized.

As light from all angular segments of the resonator is collected, the detected signal-to-noise ratio is largely improved. Our microoptic device therefore offers a promising approach towards mass-producible integration of active WGM resonators for sensor applications e. g. in a Lab-on-a-Chip where smallest possible frequency shifts need to be read out by a highly sensitive detector.

8428-38, Session 9

Optical characterization of a miniaturized large field of view motion sensor

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In this paper we discuss the geometrical and optical characterization of a miniaturized very large field of view (FOV) motion sensor inspired by the working principle of insect facet eyes. The goal of the sensor is to detect movement in the environment and to specify where in the surroundings these changes took place. Based on the measurements of the sensor, certain actions can be taken such as sounding an alarm in security applications or turning on the light in domotic applications. The advantage of miniaturizing these sensors is that they are low-cost and less visible or more esthetic compared to current motion detectors.

The sensor was designed to have a very large FOV of 124° and an angular resolution of 1° or better. The micro-optics is built up of two stacked polymer plates consisting each out of a five by five lens array. In between there is a plate of absorbing material with a five by five array of guiding channels to create 25 optically isolated channels that each image part of the total FOV of 124° onto the detector.

To geometrically characterize the lens arrays and verify the designed specifications, we made use of a coordinate measuring machine. The optical performance of the designed micro-optical system was analyzed by sending white light beams with different angles of incidence with respect to the sample through the sensor and by measuring the changes in position of the light spots visible on the detector.

First results show that for angles of incidence of ±10°, ±20° and ±30°, light spots can be seen on the detector coming from the optical channels from which we expect light.

During the presentation we will discuss the experimental results obtained with our large field of view motion sensor and compare the latter with the design. More in particular we will focus on the measured differences between designed and fabricated micro-optics and on the deviation of the light spot positions onto the detector.

8428-39, Session 9

Long single-mode waveguides made by imprint patterning for optical interconnects and sensors

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Low-loss polymeric optical waveguides were fabricated by UV-nanoimprinting. With this technique the waveguides are directly patterned during a single imprinting step on the polymeric material and cured by UV, i.e. no etching processes are needed. Because the nanoimprinting replicates the structure of the mould very accurately, waveguides having low optical attenuation is achieved with a mould having low roughness. The developed mould fabrication process takes advantage of the shadow mask lithography, resulting in waveguides having smooth surfaces and the optical loss dominated by material attenuation.

The advantages of the technology include the potential scalability onto large substrate area manufacturing and applicability for fabrication on various substrate materials. The waviness and thickness variations of the substrates can be compensated by a soft layer incorporated into the imprinting mould. For instance, printed circuit boards are interesting substrates for high-bit-rate optical interconnection applications requiring long waveguides, whereas glass and plastic sheets are interesting for sensor applications. Board-level interconnects are typically based on multimode waveguides coupled to VCSEL lasers; however, single-mode waveguides are foreseen to be needed for communication between silicon photonics devices mounted on the boards. The ability to make low-loss waveguides without top-cladding is advantageous, for instance, for bio and gas sensor applications, where the evanescent field can probe the material on the bare waveguide core. The waveguide manufacturing technology also promises for low overall costs, as it is a relatively simple high-throughput replication process.

Both ridge-type and inverted-rib-type single-mode waveguides were fabricated. In the ridge waveguide fabrication, the waveguide core is formed in the imprint pattering step and the residual layer of the same imprinting step becomes the slab layer. Whereas in the manufacturing of inverted rib waveguides, the shape of the core is first imprinted on the cladding layer (as a groove) and then the core material is applied onto the imprinted cladding, thus both filling the groove to form the waveguide core and creating the slab layer. The material used was Ormocer having low optical attenuation, e.g. about 0.06 and 0.2 dB/cm at wavelengths of 633 and 1310 nm, respectively.

Very low loss waveguides was demonstrated by fabrication of about 40-cm long ridge waveguides in a spiral shape. The width of the ridge was 2 μm and the thickness of the ridge and slab were 1.3 and 0.5 μm, respectively.

8428-40, Session 9

Novel gap alignment sensor for high-resolution proximity lithography

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The control of very small distances is essential for many applications and alignment procedures in the field of micro technology, e.g. micro lithography for MEMS or micro optics, where the proximity lithography is often used for cost effective mass fabrication. Also in proximity lithography the requirements, especially for resolution, are increasing permanently. Recently new techniques were developed to get sub-micron resolution even for larger distances between mask and substrate. But then this proximity distance has to be controlled in the micron range also. A passive and an active sensor concept have been developed based on triangulation using diffractive structures. The required sensing patterns are implemented directly in the photo mask. In the passive gap alignment the distance can be reconstructed from the resist pattern obtained as a result of a lithographic step in which the diffractive sensor structure is exposed in the Mask-Aligner. In the active configuration the proximity gap can be controlled already during the alignment procedure in prior to the lithographic exposure. A collimated laser beam irradiates a diffractive structure in the photo mask, which deflects the beam, and then the beam will be reflected from the resist coated substrate towards the mask. A second structure, which is placed in a defined distance to the first one, acts then as a ruler for the distance between mask and wafer and can be observed through the alignment microscope or a camera module.

The design and fabrication of the diffractive structures, the measurement results for the full-wafer proximity distance distribution according to the passive method as well as the realization of an active sensor module for mask aligners are presented in this paper.

8428-41, Session 9

Micro-machined optical fibre cantilever as sensor elements

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Micro-fabricated cantilevers have been reported recently as miniaturized, rapid response, ultrasensitive sensor for various chemical and bio-sensing applications. However, the alignment of the cantilever with the optical read-out system can be challenging and typically involves a bulky free-space optical detection system. We propose using cantilevers aligned to the core of an optical fibre during the fabrication process to address this issue.

Focussed Ion Beam (FIB) machining has been demonstrated as capable of fabricating fibre-top cantilevers. In this paper, we propose techniques to design and fabricate micro-cantilevers using a combination of laser machining and FIB technique to fabricate sensing cantilevers onto the end of standard and multi-core fibres (MCF). In this way the cantilever can be aligned with the core of the fibre therefore offering stable and accurate means of optically addressing the cantilever. Use of MCF offers the potential for a single probe capable of making multiple measurements in a confined measurement volume, to determine multiple species of interest, or to provide background reference measurements for example.

The detailed machining process is as follows. First of all, a rectangular ridge on top of an optical fibre is machined by a 6ps long pulse ps-laser with a repetition rate of 10KHz. After that the fibre is taken to the FIB chamber, which ion beam finishes the line-cut and forming the final cantilever. Thanks to the cost-effective ps-laser ablation, we greatly reduced the totally machining time to less than 1 hours while still maintained an optical surface quality for cantilever interrogation. In addition, we use the combination of ps-laser ablation and FIB to fabricate two parallel cantilever on top of one MCF. The dimension of the machined cantilever is 110um long, 20um wide and 8 to10um thick, which could be used as a bio-probe.

The optical cavity formed between the fibre and the cantilever is read out using low-cost tungsten halogen lamp and fibre coupled spectrometers to demonstrate a practical measurement system.This can readily achieve less than 100nm resolution using analysis based upon recovering the free spectral range using the Fast Fourier Transform to calculate the final cavity length. A real-time monitoring system is already built up by labview. We believe this resolution, coupled with appropriate cantilever design, is suitable for bio-sensing applications.

8428-43, Session 9

3D rotating octagonal micromirror optical scanner: design, fabrication, and assembly

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The design, fabrication and microassembly of a novel 3-D Rotating Octagonal Mirror (3DROM) scanner are presented in this paper. The optical scanner was constructed in a two stage process, it was first fabricated using surface micromachining PolyMUMPs fabrication process [1], and then assembled using a robotic micromanipulator system. A similar 3-D rotating inclined mirror (3DRIM) was reported in [3, 4]. A rotating polygon mirror scanner was also reported in [5] and was fabricated using SOI wafer with DRIE technique; however, the mirror does not offer high quality reflection. The 3DROM reported here was designed based on the required optical functionality for portable miniature external cavity tunable laser. This paper will present all aspects of the design, fabrication and microassembly of the 3DROM.

The 3DROM consists of a two sets of mirrors that form the eight sides of an octagonal prism, assembled on top of a rotating platform. It is capable of full 360 degree rotation using electrostatic-based actuation. It is intended for external cavity tunable laser application [2]. In order to construct the 3DROM, microassembly techniques based on the Passive Microgripper, Key and Inter-Lock (PMKIL) [6] assembly system were used to assemble microparts fabricated with PolyMUMPs. Each micropart is designed with geometrical features that make it compatible with the microassembly process, which are:

1-Tethers features to secure the mirror to the substrate through the release and grasping processes,

2-An interface feature to mate with the microgripper during the grasping process, and

3-A Joint feature to join one micropart with another micropart or to the rotating platform.

The rotating platform has a diameter of 400 microns. Four pairs of snap-key-slot joint features are designed into the rotating platform and are placed at four sides of an octagon.

The assembly process offer the flexibility of placing each feature at any location in the micropart to fit the require functionality of the proposed MEMS device. In both sets of the mirrors, the interface feature, the tether features, and the joint feature were designed to fit at the lower section of the mirror. This unique design offers an octagon prism with clear continuous apertures of 100×100 µm by each mirror. Both sets of the mirrors were released in a two step process without implementing any etch-release-holes required by PolyMUMPS. For the assembly process, the first step is to assemble four mirrors from the PM set into the rotary platform using the snap-key-lock joints. The next step is assembling another four mirrors from the CM set. Each mirror from the CM set has a slit on both sides to form inter-lock joints with the pre-assembled mirrors from the PM set. After fully assembling the 3DROM, all mirrors are in excellent vertical position to the rotating platform where the sides of each mirror is aligned with the sides of the other two mirrors having common inter-lock joints.

Mechanical testing of the 3DROM was conducted where it was successfully rotated at low speeds. The 3DROM is not tested at the designed rotation speed which is 1500 rpm as it needs special test setup in order to measure the rotation speed and will be presented at the conference.

REFERENCES

1. D. Koester, A. Cowen, R. Mahadevan, M. Stonefield, and B. Hardy, PolyMUMPs Design Handbook Revision 9.0, 9th ed., MEMSCAP, MEMS Business Unit (CRONOS), Research Triangle Park, N.C., USA, 2001.

2. A. Liu X. Zhang, “A review of MEMS external-cavity tunable lasers,” J. Micromech. Microeng., vol. 17, no. 1, pp. R1-R13, 2007.

3. M. A. Basha, N. Dechev, S. Safavi-Naeini, and S. Chaudhuri, “A scalable 1 × n optical mems switcharchitecture utilzing a microassembled rotating mirror,” IEEE J. Sel. Topics Quantum Electron.,, vol. 13, no. 2, March/April 2007.

4. M. A. Basha N. Dechev,S. Safavi-Naeini, and S. Chaudhuri, “Improved design of large 3D micromirrors for microassembly into an optical MEMS cross-connect,” in Proceedings of the SPIE, Volume 6717, pp. 67170I (2007).

5. A. Yasseen, et. al, “High-aspect-ratio rotary polygon micromotor scanners,” Sensors and Actuators A: Physical, v. 77, no. 1, 1999.

6. N. Dechev, L. Ren, W. Liu, W. Cleghorn, and J. Mills, “Development of a 6 Degree of Freedom Robotic Micromanipulator for Use in 3D MEMS Microassembly” Proceeding of IEEE ICRA, Orland, Florida, May 2006.

8428-70, Session 9

Partially athermalized waveguide gratings

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We investigated high efficiency organic-inorganic hybrid sub-wavelength binary diffraction gratings as partially athermalized waveguides by selecting appropriate optical materials. Sub-wavelength grating structures are created with electron beam lithography in HSQ resist on Si substrate. The Si substrate with binary grating structures act as the master stamp and used for the replication into thin polymer sheets with Nanoimprint lithography. The performance of the polymer grating is evaluated in terms of small spectral shifts under heating. The efficiency was determined to be least effective at temperatures 10’s of degree above room temperature. The waveguide remains thermally stable by selecting polymeric optical materials with high thermal expansion coefficients supported by a cover layer of thin amorphous inorganic optical material TiO_2 by atomic layer deposition process. The spectral shifts towards longer and shorter wavelengths were evaluated in terms of two main factors, thermal expansion coefficient TEC and thermo-optic coefficient TOC of organic and inorganic materials.

Very often inorganic guided mode resonance filters are coated with high index material like TiO2. Titanium dioxide has a negative thermo-optic coefficient i.e the refractive index decreases with increase in temperature. As a result of refractive index decrease, the spectral response of filter shifted towards shorter wavelengths (few nm). In order to stabilize the resonance position of filter in presence of heating environment, high coefficient of thermal expansion materials are employed (like optical polymers). Thereby, on rise of temperature, periodicity of grating structure increases and it responds to slightly longer wavelengths. After combination of both effects, the resonance line width is calculated to keep its resonance position without much shift in spectral response and thus originate partial athermalized devices. Calculations for transverse electric TE mode show a spectral shift of 1nm/100 °C by including both TEC and TOC effects. Experimentally obtained results revealed a spectral shift of 1nm when temperature changes from 45 to 50 °C and then remain thermally stable up to 100 °C. Experimentally obtained results are in complete agreement with the theoretically calculated results, which are demonstrated up to temperature range of 100 °C.

8428-55, Poster Session

Talbot-carpets of periodic and quasi-periodic close-packed 2D mask structures calculated by a modified Chirp-z-algorithm

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When a two-dimensional periodic mask is illuminated with a spatially coherent light source a complex 3-dimensional intensity pattern is induced by diffraction effects in the adjacent region behind the mask. This resulting,so-called Talbot-carpet,typically consists of a series of self-images of the mask structure in multiples of a well-defined distance. Furthermore, in the spatial region between the self-images also structures with fractions of the initial periodicity occur. This characteristic of the Talbot effect have attracted significant technological interest, as it allows high-frequency structuring without the need of any additional optical elements. In this contribution we simulate theoretically the resulting Talbot-carpets of different initial close-packed 2D mask structures. Especially we investigate the transition from regular periodic to quasi-periodic tessellations. In the latter case Penrose tapestry based on rhombus pairs was in the center of interest. The individual two dimensional unit cells of the mask (periodic or quasi-periodic) are decorated with different phase- and/or amplitude distributions. The numerical algorithm of our simulations is based on a modified angular-spectrum method, in which Bluestein´s fast Fourier transform (FFT) algorithm is applied. This approach allows to decouple the sampling points in the real space and the spatial frequency domain so that both parameters can be chosen independently. The introduced fast and flexible algorithm requires a minimized number of numerical steps and computation time, but still offers a high accuracy.

8428-57, Poster Session

The refractive index measurement technique based on the defocus correction method in full-field optical coherence tomography

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We propose the noble technique for the measurement of refractive index (RI) in full-field optical coherence tomography (FF-OCT). As a powerful biomedical imaging modality, FF-OCT provides noninvasive inner microstructure images of various biological samples with a submicron depth resolution. However, the RI mismatch between the biological sample and the surrounded medium makes the depth resolved en-face image out of focused in the FF-OCT system. Moreover, the FF-OCT system provides only the inner structure information of the sample. We correct the blurred image by using the angular method based on the Fresnel diffraction theory. The complex field of the sample is restored by the phase shifting method. Moreover we measure the RI by using the correction distance that is acquired from correction process in vivo. The noninvasive RI measurement and its distribution are essential to understand the optical property of a biological sample. It is also helpful for optical diagnostics and laser treatments. The Previously developed RI measurement is usually in vitro technique, or in case of in vivo RI measurement, somewhat complicated system is composed. We can measure in vivo RI only by using the FF-OCT system without any other equipment. In FF-OCT system, the higher RI of the sample then that of the surrounded medium (water or air) separates the focal plane and the coherence plane. We measure the RI of the sample by acquiring the separated distance between the focal plane and the coherence plane. We will acquire the surface and the bottom image of the USAF resolution target with facing down. The blurred bottom image through its glass material will be corrected and the index of the glass material will be measured. Finally, we will apply this technique to the biological sample and obtain the corrected en-face image and its RI.

8428-58, Poster Session

Ferrule-top nanoindentation

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Nanoindentation is used to probe mechanical properties of materials on the nanoscale. Tips of known geometry are pressed into materials while recording the force on the tip and the depth of indentation. The force indentation relation allows one to determine the Young's modulus of the sample as well as its hardness and the tip-sample adhesion energy. Conventionally nanoindentation is performed using either a direct sensing indenter or an atomic force microscope. Because of the laser alignment needed to put the setup into operation, the atomic force microscope setup cannot be operated by untrained personnel. Moreover the size of both setups, in the order of cubic decimeters, makes it impossible to use these techniques out of laboratory environments.

We have therefore explored the possibility to perform nanoindentation measurements with a new kind of atomic force microscope probes that eliminates all alignment procedures and allows ultimate miniaturization: the ferrule-top probe. Ferrule-top probes consist of a cantilever manufactured on top of a ferrule terminated optical fiber. The deflection of the cantilever is measured by interferometric technique, through the optical fiber itself, thus eliminating the need for any laser alignment. Combined with the small size and flexibility of the probes this technology could bring indentation measurements to previously unreachable areas and out of the laboratory environment.

In this poster, we present the first series of indentation measurements using a ferrule-top probe. We show the results obtained on a set of PDMS samples by a ferrule-top probe with a cantilever of 47 N/m stiffness and a spherical tip of 74 micrometer radius in both air and water and discuss future applications.

8428-59, Poster Session

Fabry-Perot tunable infrared filter based on structured reflectors

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Infrared spectrum analysis of substances and gases by extremely small and light weight spectrometers is a very time efficient and cost effective method. Micromachined tunable infrared filters based on the Fabry-

Perot-Interferometer (FPI) principle are suitable candidates for becoming the key components of such systems. Distributed Bragg Reflectors (DBRs) are applied for the reflectors in most cases. However, they lead to higher complexity of the fabrication procedure since special materials with high and low refractive index have to be used and must be patterned by photolithography.

This paper reports on the application of sub-wavelength structured single layer reflectors in a FPI in order to replace DBR. A pair of two-dimensional arrays of ring resonators was analyzed. A 100 nm thin Al layer is regularly patterned in order to form a meta-surface structure. It shows very high reflectance in a wide wavelength range.

The optical design procedure takes into account, that the Airy function describes the dependence of the stop band and the pass band characteristic on the reflector's spectral reflectance RR and spectral absorbance AR . However, RR and AR have to be determined by numerical simulation based on finite difference time domain (FDTD) analysis of the reflector arrays.

This design approach has the advantage that this optimization can be done by varying geometry parameters of lateral structures only. Moreover, the material is highly compatible to standard MEMS processes. The structures used here are circular disks and rings arranged in a 2-dimensional array. Thus, parameters to be varied are disk radius r, array pitch p and array offset o. Within the wavelength range 3...4µm, and with TFPI_max>0.6, a bandwidth FWHM 100:1 were achieved. The optimum dimensions of the metal rings have been found iteratively.

In a first technological attempt, e-beam lithography was utilized for defining of the metal ring or disk resonators. The application of imprint lithography is under investigation because it is significantly more time efficient. The device is fabricated by structuring of two silicon wafers and subsequent wafer bonding. Deep dry etching of the reflector carriers from the back side in the areas of the resonator arrays results in free standing silicon nitride membrane that carry the resonators. The elastic suspension is fabricated by dry etching also in a further step. Finally, the substrates are assembled by a wafer bonding technique utilizing a SU-8 polymer layer with a very definite thickness.

The optical performance was measured by Fourier transform infrared spectrometer and compared to the simulation results. It shows a widely good agreement between calculation and measurement.

8428-60, Poster Session

Development of glass microoptics for MidIR with hot embossing technology

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Hot-embossing (HE) is a very promising approach for low cost, mass production of a wide range of micro optical components. It is widely used for the replication of plastic micro optical components but their use in high power applications is very limited. In this paper we report on the development of diffractive and refractive micro optical components devoted to MidIR applications. As a material we use a customized tellurite and lead-bismuth-glass with high transmission in the range 0.6 - 6.0 µm. Optimization of the glass composition for a broadband transmission window is difficult due to their excessive crystallization susceptibility. It is well known for several types of soft glass (silicate, borate, phosphate) that the transition from two-component systems to multi-component systems can increase the thermal stability of the glasses. This phenomenon is also confirmed for the tellurite and heavy metal oxide glasses. In this paper we report on the optical and thermo-mechanical properties of tellurite glasses synthesized in four- and five-component oxide systems with TeO2, WO3, PbO, Nb2O3 and Na2O as well as three-component lead-bismuth-galate glasses optimised for the hot embossing technology.

Several metals and alloys were tested for their suitability as a stamping medium. Optimal performance was obtained for selected brass and steel stamps, as well as for pure silica stamps. As a technology test we have developed 1D and 2D diffractive gratings with a minimum feature size of 5µm as well as Fresnel and refractive microlenses with a diameter of 200 µm. The quality of the embossed elements was verified by comparison of the master and replicated elements using a non-contact white light interferometer. The optical performance of the selected components was tested using laser and LED mid infrared sources at wavelengths of 1.5, 2.3 and 3.1 µm. A comparison of the measured results with the simulated performance of the optimized components is presented.

8428-61, Poster Session

Optical birefringence in 2D photonic crystals

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The amplitude and the phase of the waves transmitted through 2D-Photonic Crystals (2D-PC) depend on the direction of the Electrical Field of the incident wave in relation to the symmetry axis of the 2D-PC. For certain geometries of the PC structure it is possible to obtain the same amplitude and a phase difference for the two orthogonal directions of the electric field of the transmitted waves. This phase difference can be interpreted as a form birefringence and it can be used to produce polarization elements as waveplates. In this paper, we demonstrate a technique, based in Interference Lithography, for fabrication of volumetric 2D-PCs for the visible and infrared part of the spectrum as well we measure their birefringence properties. The 2D-PCs were recorded in a thick photoresist film coated on glass substrates, by superimposition of two interference patterns. The resulting structures present a crystal axis of symmetry along the substrate surface, thus they can be considered as "infinite" along the symmetry axis of the crystal. Such fact allows the use of such structures as free space devices. The experimental measurements of 2D-PC demonstrate that phase shifts of about 50o can be achieved for the wavelength λ=633nm, that corresponds to a birefringence of about Δn = = 1.75x10-2. Numerical simulations of the structures, performed by MCWT, were used to optimize the PC parameters in order to improve the birefringence.

8428-62, Poster Session

Diffractive optics development with stack-and-draw technique

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We present a novel approach to the fabrication of diffractive optical elements (DOEs). Unlike traditional DOEs, the different phase shifts are not obtained by differences in glass thickness but through a refractive index variation obtained by using different types of glass. This approach results in a completely flat element which is easy to integrate with other optical components. For fabrication of the test DOE structures we have used the stack-and-draw technique. This method, which was originally developed for the fabrication of photonic crystal fibres, has been modified to allow the fabrication of nanostructured micro-optical components.

The fabrication procedure consists of stacking macroscopic glass rods into a preform according to the desired pattern. For the initial proof of concept trials, two different types of glass rod were used although, in principle, any arbitrary number of glass types could be exploited. Each glass rod corresponds to one 'pixel' of the diffractive optical element. The preform is then drawn-down using a fibre draw tower until the desired

feature size is reached. Finally the output rod is cut into slices which are ground and polished down to the desired thickness. Since each type of rod is characterised by a different refractive index, an optical element with a pixellated phase shift is created. The functionality of the fabricated diffractive optical element depends on the overall phase difference between pixels which is a function of the length of the component.

In this paper we present the results from proof of concept periodic chequer boards fabricated on a square and hexagonal lattice with feature sizes of 5µm and 45µm. The components were fabricated from two types of rods made of the in-house synthesised NC21 silicate glass and the off-the-shelf F2 lead-silicate glass.

The measured characteristics of the fabricated components are presented and verified against modelled performance. The influence of fabrication-induced structure distortions on the optical performance of the components is discussed.

8428-63, Poster Session

Ultra compact switching matrixes on InP

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The aim of the research is to design and fabricate a switching matrix permitting a microwave delay for the control of antennas array into embedded systems.

The matrix consists of two parts: first part is an "active region" with Digital Optical Switches (DOS) in InP allowing the operation of the device and the second one is a "passive region" in dielectric material guiding the light properly after switching. Thereby, the coupling has to be done between switches and dielectrics waveguides with a high optical confinement on same InP substrate to permit a monolithic integration.

DOS are a Y junction in InP integrated optics including a P-I-N junction in each output arms to allow carrier injection. In principle, the optical signal is equally separated into the two output branches without current injection, but when we inject current into one output arm, we obtain a lower refractive index and the optical signal is redirected into the other branch.

Simulations were executed to determine the geometry of dielectric waveguide with three dimensional beam propagation method (3D-BPM). A buried guide which constituted of a silicon nitride core and silicon oxide cladding materials with a nanotaper input which is an inverted taper (a tip) improving the fiber coupling (+50%) for these monolithic integration devices at 1.55µm wavelength.

Currently, the active structure used is an epitaxy grown using molecular beam epitaxy on n+ InP substrate. The device fabrication is in progress and the results aimed such as optical isolation (> 30dB), speed switching (nanoseconds), insertion losses (16dB), low consumption (45mW), no noise, polarization sensitive (10dB) and total length for the matrix (2.5mm).

To conclude, the coupling must be very good (with low losses) between each transition as Optical Fiber/Active structure (OF/AS) and Active structure/ Dielectric nanoguide (AS/DN). These tests realized provide results such as coupling losses of 1.8dB (OF/AS) and 0.5dB (AS/DN).

8428-64, Poster Session

Development of light-scattering thermal cross-link package material based on self-assembly in optical devices

S. Takei, Toyama Prefectural Univ. (Japan)

We present investigations of light-scattering thermal cross-link package material based on self-assembly in optical devices.

Thermal cross-link package materials based on self-assembly indicated good nano regularly-structured patterning for light-scattering, excellent environmental stability of optical parameters, and solvent intermixing resistance after thermal cross-link reaction.

The developed light-scattering thermal cross-link package materials based on self-assembly is one of the most promising processes ready to be incorporated into the mass production of patterning light-scattering optical layer for advanced electronic devices such as display, light emitting diode and solar cell.

8428-65, Poster Session

Development of plant-based resist material derived from biomass on hardmask layer in ultraviolet curing nanoimprint lithography

S. Takei, Toyama Prefectural Univ. (Japan)

Nanopatterning printability due to nanoimprint resist volumetric shrinkage was one of key to achieve high resolution and quality of nanoimprint lithography. The new ultraviolet curing plant-based resist material derived from biomass was investigated to achieve high quality of sub-100 nm line and multiple nanoimprint patterning images in the optimized conditions of ultraviolet curing nanoimprint lithography for the optical films containing light-emitting diodes, solar cell devices, actuators, biosensors, and micro electro mechanical systems. The newly plant-based resist material derived from biomass is expected as one of the defect less nanoimprint lithographic technologies in next generation optical devices.

8428-66, Poster Session

Development of water-developable resist material derived from biomass in multilayer processes of advanced lithography

S. Takei, Toyama Prefectural Univ. (Japan)

A water-developable resist material in the developable process of advanced lithography for mass production of optical devices is expected, instead of organic solvents for environmental affair, safety, easiness of handling, and health of the working people. A novel high-sensitive negative type of plant-based resist material derived from biomass on hardmask layer was developed and demonstrated in the multilayer processes of advanced lithography. The material design concept to use the plant-based resist material derived from biomass was proposed. The 1 µm line patterning images with highly efficient crosslinking properties and lower film thickness shrinkage were provided by specific process conditions of multilayer processes of advanced lithography for optical devices.

8428-67, Poster Session

Exploration of a microdeformable liquid mirror device

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A deformable mirror based on the principle of total internal reflection (TIR) of light from an electrostatically deformed liquid-air interface was realized and used to perform closed-loop adaptive optical correction on a collimated laser beam aberrated by a rotating phase disk. The liquid system was characterized including open- and closed-loop frequency responses, determination of rise-times, the damping times of the liquid, and the influence of liquid surface motion in the absence of external optical aberrations. The dynamic behavior of the liquid is determined on the large scale by gravity (gravity waves) and on a small scale by surface tension (capillary waves). In our case the resonant characteristics of the system were dominated by gravity and the results of the experimental realization were found to be in good agreement with the predictions of the theory. A miniaturization of the system promises to eliminate the dominant gravity waves and considerably reduce the errors introduced by ambient vibrations. This paper explores the possibilities and requirements for such a micro device.

8428-68, Poster Session

Giant increase of photorefractive effect in Fe:LiNbO3: a new approach

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In recent times photorefractive effect attracted significant interest due to its potential application for the realization of holographic optical elements, optical memories, phase conjugated devices and so on 1. Among the other photorefractive materials, lithium niobate doped with iron occupya special role, because of its high photorefractive sensitivity coupled with an excellent combination of advantageous functional properties and commercial availability. Despite of its potential, the success of this material is hindered by its response time, which is slow compared to that of other photorefractive materials. General approaches to overcome this problem amounts to co - dope the material with one or more elements in order to shorten the characteristic time of the photorefractive response by increasing its photoconductivity 2. In this work we present an alternative approach, based on a decrease of the photoconductivity. We show that, by using this approach, holograms with refractive index modulations as high as 10-3 can be written in few seconds using low power lasers.

References

1 P. GUNTER, and J. HUIGNARD, Photorefractive Materials and Their Applications 2: survey of applications, Springer Topics in Applied Physics 61, (Springer, Berlin, 1988).

2 T. Volk, and M. Wöhlecke, Lithium Niobate : Defects, Photorefraction and Ferroelectric Switching, (Springer, Berlin, 2008).

8428-71, Poster Session

Investigation on 2D disks and stadiums micro-resonators structures based on UV210 polymer

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We report on the design and the overall realization of micro-resonators based on the development of adequate processes on UV210 polymer. These micro-optical structures are developed by deep ultraviolet lithography allowing fabrication of nano-structured devices by mean of low cost and reproducible processes. Two families of resonant micro-structures shaped on disk and stadium with various sizes are investigated. Structural and optical imaging characterizations have been carried out to ensure their ability as resonant integrated micro-structures. At first, scanning electron microscopy (SEM) and Nomarsky microscopy studies confirm the UV-light process resolution down to 450 nm developed on UV210 polymer. Then, optical characterizations have been performed as regards intensity and spectral properties of such micro-resonators. Field intensity measurements in visible and infrared range have been realized and validate the aptitude of the micro-structures to propagate and to allow an evanescent photonic coupling between waveguides and micro-resonators. Finally, spectral analyses demonstrate the presence of optical resonances with 1.45 nm and 2.19 nm free spectral range values for respectively disk and stadium micro-structures. The UV210 polymer appears appropriate for the realization of micro-structures requiring a few hundred nanometers gap-scale while maintaining adequate spectral properties for versatile applications in telecommunication, metrology and sensors.

8429-01, Session 1

On the design of spherical gradient index lenses

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The classical spherical gradient index (GRIN) lenses such as Maxwell Fish Eye lens, Eaton lens, Luneburg lens, etc. are calculated using the Abel integral equation. Each lens is fully defined by a function called the angle of flight which describes the ray deflection through the lens. In this paper, the design of the GRIN lenses is reorganized in a new way. The radial refractive index distribution is obtained by applying a linear integral transformation to the angle of flight. The interest of this formulation is in the linearity of the integral transformation which allows us to derive solutions from linear combinations. Beside the review of the classical GRIN designs, this novel procedure is used to solve other GRIN lenses defined by the Abel integral equation with fixed limits, which is an ill-posed problem.

8429-02, Session 1

3D metrology system based on a bidirectional OLED microdisplay

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Expanding demands on manufacturing technology increase the requirements on necessary non-contact metrology. Several optical metrology systems are based on separated imaging (e.g. camera unit) and image generating units (e.g. projection unit). This fact limits the geometrical miniaturization of the system.

We present a compact, highly integrated 3-D metrology system applying on the fringe projection principle using a bidirectional OLED microdisplay developed by Fraunhofer IPMS. This microdisplay combines light emitting pixels called OLED microdisplay (projection unit) and light detecting pixels called photo diodes (camera unit) on one single device, realized by the OLEDs-on-CMOS-technology. This technology provides the opportunity for a further miniaturization of optical metrology systems.

The 3-D metrology system is based on fringe projection onto the surface of the measurement object. The fringes will appear deformed when observed from a different angle (triangulation angle). From the deformation of the fringes the 3-D coordinates of all visible points can be calculated and thus the object shape can be determined.

For the fringe projection and imaging path, separate lenses are necessary. Several optical system configurations, for example the used of macro- and / or micro-optics for the compact optical system will be discussed.

Due to the application of the bidirectional OLED microdisplay the fringe generating elements and the detectors will be combined into one single device. Therefore an ultra-compact and solid system concept for 3-D surface metrology is possible.

8429-03, Session 1

Integrating the advanced human eye model (AHEM) and optical instrument models to model complete visual optical systems inclusive of the typical or atypical eye

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PURPOSE: To present a commercially available optical modeling software tool to assist the development of optical instrumentation and systems that utilize and/or integrate with the human eye. METHODS: A commercially available flexible eye modeling system is presented, the Advanced Human Eye Model (AHEM). AHEM is a module that the engineer can use to perform rapid development and test scenarios on systems that integrate with the eye. Methods include merging modeled systems initially developed outside of AHEM and performing a series of wizard-type operations that relieve the user from requiring an optometric or ophthalmic background to produce a complete eye inclusive system. Scenarios consist of retinal imaging of targets and sources through integrated systems. Uses include, but are not limited to, optimization, telescopes, microscopes, spectacles, contact and intraocular lenses, ocular aberrations, cataract simulation and scattering, and twin eye model (binocular) systems. RESULTS: Metrics, graphical data, and exportable CAD geometry are generated from the various modeling scenarios.

8429-05, Session 1

All aspect correction of canopy induced optical abberations in electro-optical systems

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Electro-optical imaging systems being used by pilots in tactical aircraft, view imagery through the aircraft canopy. Unfortunately the canopy acts as a highly aberrated lens in the electro-optical sensor's optical path. Because the canopy primary function is to serve, first and foremost as an aircraft component, considerations like minimizing the drag co-efficient and the ability to survive a bird strike take precedence over optical considerations. This paper describes how the authors modeled the optical characteristics of an aircraft canopy and subsequently designed and prototyped an optical corrector to negate the canopy effects. The canopy induced aberrations for various viewing geometries through the canopy were modeled, for various electro-optical system entrance pupil diameters. The model was used to develop an optical sub-system that compensates for those introduced by the canopy. The optical compensator provided the means to significantly reduce the effect of the canopy "lens" on the electro-optical system performance, regardless of the Electro-Optical system position and line-of-sight relative to the canopy. This paper describes how we approached the problem and were able to compensate for the optical contributions in a high resolution imaging system. The aberrations introduced by the canopy are a function of where the sensor is located and what portion of the canopy the sensor is imaging through. Consequently the canopy effects vary considerably. The authors have developed a general solution that is not orientaion specific. Correction at several E-O sensor locations is demonstrated.

8429-06, Session 2

Electro-optically actuated liquid-lens zoom

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Progressive miniaturization and mass market orientation denote a challenge to the design of dynamic optical systems such as zoom-lenses. Two working principles can be identified: mechanical actuation and application of active optical components.

Mechanical actuation changes the focal length of a zoom-lens system by varying the axial positions of optical elements. These systems are limited in speed and often require complex coupled movements. However, well established optical design approaches can be applied. In contrast, active optical components change their optical properties by varying their physical structure by means of applying external electric signals. Zoom-lenses benefit from active optical components in two ways: first, no moveable structures are required and second, fast response characteristics can be realized.

Recent optical design examples making use of active optical components result in sophisticated solutions suffering from insufficient synthesis of active systems behavior. The high degree of complexity makes these examples not conveniently applicable for pre-commercial development of zoom-lenses demanding more simplified and cost-effective system designs.

In this paper, a new approach will be discussed concerning the systematic development of an electro-optical actuated liquid-lens zoom. A more generalized modular design concept leads to enhanced synthesis of the system behavior and further to a more targeted integration of active components.

8429-07, Session 2

Method to determine influence functions for complex optical systems

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Since optical systems become more complex and accurate, the need for optical modeling increased for which ray-tracing software like Code V and Zemax have been developed. Although the software is very useful for optimization and analysis of optical systems, the interface with other software such as Matlab or FEM packages is limited and a user has to be an expert to use the ray-tracing software. Therefore we present a fast and easy method to determine the influence function that relates the change of the wavefront to the deformation of an optical surface. This method can be used by advanced ray-tracing users to do preliminary calculations before designing the optical system or even by people with no experience in ray-tracing software as a tool to integrate subsystems in the optical system or to interpret the optical system.

The proposed method uses a coordinate transform that relates the coordinates of an optical component to the coordinates in the pupil. This coordinate transform is derived with the help of the paraxial approximation, using optical data from the ray-tracing software. With this coordinate transform the deformation of an optical component can be related to the wavefront change and can be used to model thermal aberrations, mirror vibrations, or the influence of manufacturing errors, without using optical ray-tracing programs.

In order to demonstrate this method, we selected a projection optical system that is known from literature and consists of six mirrors. We parameterize this optical system, with the help of the proposed method, using the optical data. Finally we illustrate the method by calculating the wavefront aberration as a result of a mirror deformation.

8429-08, Session 2

Using Fermat's principle to design two free-form lens profiles for optimal imaging performance

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In this work, a new two dimensional optics design method is proposed that enables the coupling of three ray sets with two lens surfaces, especially important for optical systems designed for wide fields of view and with clearly separated optical surfaces. However, this can only be achieved if different ray sets will use different portions of the lens surfaces. Optical systems, where different incident directions use different portions of lens' surfaces, are widely known. E.g., field-flattener lenses are used in binocular designs and in astronomic telescopes to improve edge sharpness and lower distortion. Aperture stops in imaging systems often target the same objective. Based on a very basic example of a single thick lens, the Simultaneous Multiple Surfaces design method in two dimensions (SMS2D) will help to provide a better understanding of the practical implications on the design process by an increased lens thickness and a wider field of view.

Fermat's principle is used to deduce a set of functional differential equations fully describing the entire optical system. The transformation of these functional differential equations into an algebraic linear system of equations allows the successive calculation of the analytic Taylor series coefficients up to an arbitrary order. This implemented general analytical solution makes it possible to calculate the exact lens profiles. For obvious reasons, it is only possible to calculate a finite number of initial terms of the Taylor series. Such a function is called a Taylor polynomial and will be the only approximation made. Ray tracing results for calculated 15th order Taylor polynomials describing the lens profiles demonstrate excellent performance and the versatility of this new analytical optics design concept. Furthermore, Taylor's remainder theorem provides quantitative estimates on convergence and the approximation error of the function by its Taylor polynomial.

8429-09, Session 2

Correction of a liquid lens for 3D imaging systems

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3D imaging systems are currently being developed using liquid lens technology for use in medical devices as well as in consumer electronics. Liquid lenses operate on the principle of electrowetting to control the curvature of a buried surface, allowing for a voltage-controlled change in focal length. Imaging systems which utilize a liquid lens allow extraction of depth information from the object field through a controlled introduction of defocus into the system. The design of such a system must be carefully considered in order to simultaneously deliver good image quality and meet the depth of field requirements for image processing. In this work a corrective model has been designed for use with the Varioptic Arctic 316 liquid lens. The design is optimized for depth of field while minimizing aberrations for a 3D imaging application. The modeled performance is compared to the measured performance of the corrected system over a large range of focal lengths.

8429-10, Session 2

Optical design of a multichannel multiresolution imaging system

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Multi-channel imaging systems are offering an alternative for classic wide field-of-view cameras. These systems can have a compact form-factor and are low-cost. In this work, we focus on designing each imaging channel of such a multi-channel system in such a way that different channels have a different angular resolution and field-of-view. Specifically, our aim is to realize a smart imaging system that is able to resolve details of a small region of interest through the channel that has the highest angular resolution while controlling the surrounding region through the channel that has the largest field of view. An interesting feature of such a multi-channel, multi-resolution imaging system is that different image processing algorithms can be applied at different segments of the image sensor. For example, a face detection algorithm could be implemented on the image information that is imaged through the optical channel with the highest angular resolution and a motion detection algorithm could be implemented on the image information that is imaged through the optical channel with the highest field-of-view. We have designed a three channel imaging system where each optical channel consists of four aspheric lens surfaces. The design was analyzed

and optimized with CODE V optical design software. All three imaging channels share one image sensor which has 1440x960 pixels and a pixel size of 10µm. The first channel has the highest angular resolution (0.0096 degree) and smallest field-of-view (2x3.5 degree). The second optical channel covers an equal image sensor segment as the first channel, but it has a larger field-of-view and lower angular resolution. The third channel covers the largest portion of the image sensor. It has the highest field of view (2x40 degree) and lowest angular resolution (0.078 degree). All imaging channels have diffraction limited performance ensuring a good overall image quality.

8429-11, Session 3

Optical simulations for Ambilight TV systems

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Ambilight is a unique Philips feature, where RGB LEDs are used to create a dynamic light halo around the television. This extends the screen and hence increases the viewing experience, as it draws the viewer more into the action on the screen. As such the feature receives very positive consumer feedback. However, implementing Ambilight in the increasingly stringent design boundary conditions of a slim and thin TV set is a challenging task.

Optical simulations play a vital role in each step of the Ambilight design process. Ranging from prototype to final product, we use simulations, next to optical measurements, to aid the choice of LEDs, optical materials and optical systems during different phases of the design process. Each step the impact of the optical system on the mechanical design and TV set dimensions need to be taken into account. Moreover, optical simulations are essential to guarantee the required optical performance given a big spread in LED performance, mechanical tolerances en material properties.

Next to performance, optical efficiency is also an important parameter to evaluate an optical design, as it establishes the required number of LEDs and the total LED power. As such optical efficiency defines the thermal power which needs to be dissipated by the LED system.

The innovation roadmap does not stop here. For future systems we see a miniaturization trend, where smaller LED packages and smaller dies are used. This evolution makes the impact of mechanical tolerances on the optical design more severe. Consequentially, this approach poses a whole new challenge to the way we use optical simulations in our design process.

8429-12, Session 3

Phase space optics: an engineering tool for illumination design

A. M. Herkommer, D. Rausch, Univ. Stuttgart (Germany)

Aberration theory provides solid ground for the layout and development of optical imaging systems. Together with general design rules it will guide the optical engineer towards a valid starting point for his system. Illumination design is quite different: Often first system layouts are based on experience, rather than on a systematic approach. In addition radiometric nomenclature and definitions can be quite confusing, due to the variety of radiant performance definitions. Also at a later stage in the design, the performance evaluation usually requires extensive statistical ray-tracing, in order to confirm the specified energetic quantities. In general it would therefore be helpful for illumination designers, especially beginners, to have an engineering tool, which allows a fast, systematic and illustrative access to illumination design problems.

Within this presentation we show that phase space methods can provide such a tool and moreover allow a consistent approach to radiometry. In order to confirm this, we first recall the concept of phase space and its relation to radiometry and radiance. In a second step, we consider light propagation through optical systems within phase space and illustrate the corresponding transformations of the input radiance distribution. By employing these basic rules we show that even complex light mixing components, like integrator rods and optical arrays, can nicely be analyzed in phase space, without the necessity of tracing millions of rays. An analysis of representative ray trajectories in phase space can thus provide insight even into complex systems. As an example we illustrate lithography illumination systems and analyze the different architectures and their limitations. Additionally the illustration of diffractive optical elements and beam shapers will prove that we are able to treat etendue-increasing as well as entendue-conserving illumination systems.

In summary the concept of phase space allows an alternative and constructive approach for solving radiation transfer problems: The desired target illumination distribution represents a certain phase space pattern and thus the optimized illumination system corresponds to the most efficient transformation of the source distribution into this target pattern.

8429-14, Session 3

Thermo-optical (TOP) analysis by coupling FEM and ray tracing

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The imaging quality of optical systems used for laser beam guiding and shaping can be affected by thermal effects. The temperature dependency of the refractivity and particularly the influence of thermal gradients on ray propagation lead to complex wavefront distortions and thus to a reduced imaging quality. Hence, optical systems with high thermal loads require a thermally stable optical systems design.

Although commercially available ray tracing software is able to consider homogeneous temperature variations such as different ambient temperatures, the possibility of analyzing arbitrary thermal gradients is still in its infancy. Despite of different approaches, demonstrated in the past twenty years, there is still no prevalent engineering solution for a coupled thermo-optical (TOP) simulation with the ability of analyzing and especially optimizing thermally aberrated systems.

Our approach for realizing a TOP analysis is based on three steps: The optical system design is realized in a ray tracing simulation software which provides information on the local absorption. These absorption values are passed to a FEM simulation which determines the temperature distribution. The final step combines all information back into the ray tracing software and enables an analysis and optimization of the system.

Besides the design and analysis of thermally influenced laser systems, these algorithms can be applied onto any other thermally aberrated optical systems such as in lighting technology. Moreover, this general description can also be applied onto non-thermal effects which modify the refractivity. This includes mechanical stresses or inhomogeneities in plastic lenses due to injection moulding processes.

The requirements for coupling commercial FEM and ray tracing simulation software will be discussed. Furthermore, an approach to consider results, computed on FEM grid nodes, as scattered data and use a two-space dimensional approximation technique with the potential for a 3D extension will be demonstrated.

8429-15, Session 3

LED street lighting: modeling and design

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The superior performance of light-emitting diode (LED) street illumination is attracting significant attention. LED luminaires for road lighting have the potential to deliver precise beam patterns to minimize light pollution, increase comfort and visibility, and maximize efficiency by directing light to the appropriate area. In this presentation, we provide a simplified theoretical platform for the light management, which provides guidance toward high performance optical designs. It is a set of simple but accurate equations for photometric modeling.

We begin with a simple equation of the illuminance spatial distribution in function of the Cartesian coordinates on the floor. It is an analytical model of the two-dimensional illuminance map of the street. The equation depends on important parameters such as: the lamp height (pole), the tilt (lamp angle), and the angular intensity profile of the lamp (radiation pattern).

Second and more important, we derive an equation for the ideal radiation pattern of the LED luminaire that achieves both perfect optical efficiency and perfect illumination uniformity on several practical scenarios. Recently, several numerical methods to obtain the optimal radiation pattern have been reported in the literature, but all of them are not perfect and somehow difficult to implement. Some of these methods use linear algorithms, other non-linear algorithms, and the most sophisticated implement genetic algorithms. Here we report an analytic, simple and exact solution by reversing a perfectly efficient and uniform illuminance function.

And third, simple conditions for achieving maximum efficiency and uniformity through the street and their impact on various pole configurations are included within the theory presented here. We analyze several system arrangements of practical interest, for example: (a) one single luminaire; (b) two luminaires in a row; (c) two luminaires, each one in opposite side of the road; (d) four luminaires in a row; (e) two pairs of luminaires, each couple in the opposite side of the street; (f) the zig-zag arrangement of luminaires. We visually illustrate all the reported design tools for many representative lighting cases.

8429-75, Session 3

Simulation of the multicomponent radiation source with the required irradiance and color distribution in the working area

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Development of semiconductor light-emitting structures production technology led to the use of these products in a variety of display systems and radiation sources for special purposes, such as in automatic systems for industrial control, and optoelectronic color analysis systems.

The undoubted advantages of LED technology are the possibility of combining high radiation power with any form of its spatial distribution and large variety of colors in a wide range of brightness. But if it is needed to provide the certain irradiance or color distribution at a given distance from radiation source (for example in the analysis or in the observation zone) habits of mentioned technology became a focus of the interest.

The present work deals with the mathematical description of the multicomponent line or matrix radiation source.

In the proposed model the form of the spatial light distribution at a predetermined distance from the source is determined by the number and relative position of its components, functions describing the optical properties of the elements and by the distance from the source to working area. Linear combinations of the Lambert, Gaussian or other dependencies can be used for describing radiation indicatrices of individual source elements.

For radiation source simulation, comprising radiating elements with different emission spectra, and getting certain color distribution in the working area the distribution combination of three (red (R), green (G), blue (B)) or six (red (R), green (G), blue (B), yellow (Y), cyan (C) and magenta (M)) color components is used. The superposition of individual elements spectra is taken into account.

It is shown that there is the possibility to achieve color mixing by varying the parameters (matrix dimension, the distance between elements in the matrix, the distance from the source to the working area, etc.) and thus to realize source color control.

8429-16, Session 4

Extreme super-resolution using the spherical geodesic waveguide

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In 2009 Leonhardt demonstrated that a 2D gradient index lens known as Maxwell Fish Eye (MFE), can transport perfectly an outward (monopole) 2D Helmholtz waves of arbitrary frequency, generated by a point source, towards a “perfect point drain” located at the corresponding image point. Moreover, a prototype with wavelength/5 super-resolution property for one microwave frequency has been manufactured and tested (Ma et al, ArXiv:1007.2530v1). However, neither software simulations nor experimental measurements for a broad band of frequencies have yet been reported. Here we present an analysis of the super-resolution properties of a device, equivalent to the MFE, known as Spherical Geodesic Waveguide (SGW). A microwave circuit comprising three elements: the SGW, the source and the drain (two coaxial probes) is designed and simulated in COMSOL. The simulations have shown extremely high super-resolution up to wavelength/3000 close to a set of discrete frequencies. Out of these frequencies, the SGW does not show super-resolution.

8429-17, Session 4

Elementary field method simulations for broad area laser diodes

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Simulation of partially coherent light can be mathematically demanding. In traditional Wolf’s coherent mode representation light field is expressed as uncorrelated superposition of fully coherent field modes [1]. In Wolf’s method every mode may have different functional form and weight. Although the method is accurate and physically intuitive the difficulty is finding these modes. In elementary mode method every mode has the same form but they are spatially shifted in respect to each other. This method is not rigorous, but it works with wide range of light sources. The advantage of the method is that elementary modes can be often calculated from relatively simple measurement data, and in free space it is enough to calculate propagation for single mode only once. [2-4]

We represent numerical simulations to compare these two methods, and evaluate how accurate elementary mode method is with broad area lasers. For first near field is expressed as a superposition of modes with sinusoidal spatial amplitude inside the laser resonator and zero outside. Every mode has a different number of intensity maxima, and they are propagated in free space. Intensity in near and far field is calculated, and from this information functional form and weight for elementary modes can be calculated. After this elementary modes are shifted and propagated. Finally intensity and decree of coherence calculated with these two methods are compared. All simulations were done for 1D light source for simplicity and because of the shape of the laser resonator.

We notice that the results are very consistent. This confirms that necessary information for elementary modes can be obtained with simple intensity measurements instead of more complicated coherent measurements, at least if field is behaving nicely enough.

References

[1] E. Wolf, J. Opt. Soc. Am., 72, 343-351, 1982

[2] F. Gori and C. Palma, Opt. Commun., 27, 185-188, 1978

[3] P. Vahimaa, and J. Turunen, Opt. Express, 4, 1376-1381, 2006

[4] J. Turunen, Journal of Modern Optics, 58, 509-528, 2011

8429-18, Session 4

Propagation of non-paraxial fields by parabasal field decomposition

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The propagation of harmonic fields through homogeneous media is an essential simulation technique in optical modeling and design by field tracing, which combines geometrical and physical optics. For paraxial fields the combination of Fresnel integral and the Spectrum of Plane Waves (SPW) integral solves the problem. For non-paraxial fields the Fresnel integral cannot be applied and SPW often suffers from a too high numerical effort. In some situations the far field integral can be used instead, but a general solution of the problem is not known.

It is useful to distinguish between two basic cases of non-paraxial fields: 1) The field can be sampled without problems in the space domain but it is very divergent because of small features. A Gaussian beam with large divergence is an example. 2) The field possesses a smooth but strong phase function, which does not allow its sampling in space domain. Spherical or cylindrical waves with small radius of curvature are examples. We refer to such fields as fields with a smooth phase term. The complete phase is the sum of the smooth phase term and the residual.

For both cases we present a parabasal field decomposition, in order to propagate the field. In the first case we perform the decomposition in the Fourier domain and in the second case in the space domain. For each of the resulting parabasal fields we separate a linear phase factor which has not to be sampled. In order to propagate the parabasal fields we present a rigorous SPW operator for parabasal fields, which can handle the linear phase factors without sampling it at any time. We show that the combination of the decomposition and this modified SPW operator enables an efficient propagation of non-paraxial fields.

8429-19, Session 4

Efficient and rigorous propagation of harmonic fields through plane interfaces

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The interaction of a plane wave with a plane interface is well known and standard in optics education. The spectrum of plane waves (SPW) decomposition allows the generalization of the results for one plane wave to general harmonic fields in principle. Based on this idea we present an efficient technique to propagate arbitrary harmonic fields through plane interfaces.

In the simplest case, the harmonic field is given on the plane interface and the transmitted and reflected fields are to be computed. For this purpose, the spectrum of plane wave decomposition can be applied and it yields a fast and rigorous method. We refer to this technique as plane interface propagation method. In general we cannot assume that the harmonic field is known on the interface. For instance let us consider a laser beam, given in some input plane, which hits a prism under some angle. That is, the input plane and the entrance interface of the prism are not parallel. So, standard propagation techniques, for example the SPW integral, cannot be applied in order to compute the field on the entrance interface, because they propagate between parallel planes only. That is why we propagate the field first to the entrance interface but into a plane which is not parallel to it. Then, in a second step, we have to rotate the field into the entrance interface.

We present such a rotation technique for general harmonic fields. This procedure can process linear phase factors of the input field without its sampling, which allows fast rotation of parabasal fields. That in particular also enables the rotation of fields with for instance a strong spherical phase. To this end the field is decomposed into parabasal fields before its rotation. In conclusion in any case we can provide the field on the plane interface and therefore we can apply the plane interface propagation method to compute reflected and transmitted fields. We discuss the techniques in theory and at examples.

8429-20, Session 5

Optical modelling of silicon thin film solar cells by combination of the transfer matrix method and the Raytracer algorithm

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The aim of this work is to develop a fast and easy optical method for modelling silicon thin film solar cells with Sentaurus TCAD from Synopsys.

Optical modelling of silicon thin film solar cells needs to fulfill several criteria: Interference effects due to layer thicknesses in the range of the wavelength, as well as scattering effects at rough interfaces need to be taken into account. The Finite-Difference Time-Domain (FDTD) method and other rigorous algorithms solve the Maxwell equations and can fulfill these requirements. However the demand on the hardware and the simulation time is comparably high. To overcome these drawbacks we combine the Transfer Matrix Method (TMM) and the Raytracer algorithm. In contrast to the semi-coherent optical model suggested by J. Krc, the separation of the incident light in a specular coherent and a diffuse scattered part takes place before the light enters the cell. Though this approximation is physically less correct, it results in very good agreement with the experimental data.

The function which separates the coherent light as input to the TMM from the scattered light as input to the Raytracer is called the integrated haze. This function is the only fit parameter of the model. It is correlated with the number of interfaces in the device and with the wavelength dependant haze measured on the transparent conductive oxide substrate.

The combined model is verified by comparison to experimental data of an amorphous thin film solar cell series with varying thicknesses of the intrinsic layer on different substrates. In order to test the combined model independently from the input parameters we also compared the simulation results with complex FDTD simulations.

8429-21, Session 5

A simulation procedure for light-matter interaction at different length scales

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Optimizing the properties of optical and photonic devices calls for the need to control and manipulate light within structures of different length scales, ranging from sub-wavelength to macroscopic dimensions. Working at different length scales, however, requires different simulation approaches, which have to account properly for various effects such as polar-ization, interference, or diffraction: At dimensions much larger than the wavelength of light common ray-tracing (RT) techniques are conveniently employed, while in the sub-wavelength regime more sophisticated approaches, like the so-called finite-difference time-domain (FDTD) technique, are needed. Describing light propagation both in the sub-wavelength regime as well as on macroscopic length scales can only be achieved by bridging between these two approaches. Unfortunately, there are no well-defined criteria for a switching from one method to the other, and the development of appropriate selection criteria is an important issue to avoid a summation of errors.

In this contribution we present a simulation approach for combining simulation tools of classical ray-tracing with those of the finite-difference time- domain (FDTD) approach. Generally, the interface between RT

and FDTD is restricted to very small areas. Nevertheless, many optical devices use e.g. diffractive optical elements (DOEs) having comparably large areas in the order of 1-2 mm². Therefore, one has to develop strategies in order to handle the data transfer between FDTD and RT for such large structures. Our approach in this regard is based on the symmetries of the structures. In this way we can use programs like e.g. MATLAB to replicate the nearfield of a single structure and to merge it to the nearfield of a larger area. Comparisons of RT and FDTD simulations in the farfield can be used to validate the physical correctness of this approach. In this way, we are able to optimize light propagation effects at both the macro- and microscale and to exploit their whole potential for the manipulation and optimization of optical and photonic devices.

8429-22, Session 5

Influence of nonlinear effects in WDM system with non-equidistant channel spacing using different types of high-order PSK and QAM modulation formats

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The objective of this paper is to investigate nonlinear effects in Wavelength-Division Multiplex (WDM) systems in the case when different types of high-order M-PSK and M-QAM modulation formats for various structures of channel spacing are used optical signals. In general, the degradation mechanisms are caused by transmitted optical signals and their impact on each optical channel in WDM can be very different. Therefore, it is suitable to investigate possibilities for channel arrangement from the point of view of equidistant and non-equidistant channel spacing, respectively, what would lead to the suppression of nonlinear effects. In this article we investigate new types of high-order modulation formats that have ability for increasing of spectral efficiency and total improvement of performance of the transmission WDM system. The attention is put on two classes of channel spacing in WDM system, equidistant channel spacing (Δf = 100, 50, 25 and 12.5 GHz) and non-equidistant channel spacing ($\Delta f \neq$ const.), respectively. For investigation of signal propagation the numerical model is created. The model is based on mathematical method Symmetrical-Split Step Fourier Method (S-SSFM), which is utilized for solving the coupled nonlinear Schrödinger´s equations (CNLSE) describing the transmission of signals in multichannel systems. The results of the created numerical model are analyzed, compared to each other and interpreted in a way that leads to the determination of suitable high-order modulation formats and we try to propose the optimal arrangement of optical channels in WDM system. The key issue is to suppress the impact of nonlinearities on modulated signals for each channel with respect to the employed types of digital modulation formats, various system parameters, different types of optical fibers and localization of reference channel in the wavelength area.

8429-23, Session 5

Generation of complex beams by means of polarization holograms

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The experimental generation of complex beams is an important topic in optics. In this work we present the experimental generation of complex beams by means of a polarization holographic technique. Here we record polarization holograms on highly polarization sensitive materials. Based on the unique properties of these holograms, the amplitude, phase, and polarization state of the incident beam can be managed. In particular we show the generation of high quality nondiffracting beams.

8429-24, Session 5

Modeling of nano-optical features for emission and absorption enhancement in light-emitting diodes and solar cells

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Many recent advances in solar energy and light-emitting diode (LED) technology are based on sub-wavelength optical features and nano-photonic effects. Owing to the fundamental reciprocity between absorption and emission in optically active materials, similar features e.g. coarsened surfaces and optical gratings can be used both to enhance light trapping and absorption in solar cells and to increase light extraction and emission in LEDs. We present a unified radiative transfer model for the energy exchange in light emitting and absorbing semiconductor devices and discuss on the application of nano-optical concepts in LEDs and solar cells. We show that similar to the absorption in solar cells, the emission in LEDs can be enhanced up to the ergodic limit by incoherent methods, e.g. by surface roughening and beyond that by employing coherent, wave-optical effects in nano-structured devices. We apply the model to simulate the light extraction in current state-of-art LEDs and further discuss on the application of plasmonics and optical gratings in LEDs.

8429-25, Session 5

Acousto-optical dispersive delay lines for femtosecond laser systems

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Application of acousto-optical methods of ultrafast pulse shaping resulted in a serious progress in that field during past years. For most practical issues, quasicollinear diffraction of light by chirped ultrasound is used. We report on recent advances in design of acousto-optical light dispersive delay lines for various architectures of CPA and OPCPA laser systems. The achievements are based on a novel theoretical approach that combines the phenomena of diffraction and dispersion of light pulses in the crystals. Thus, the influence of group delay on the diffraction parameters is taken into consideration. We developed high-performance acousto-optical delay lines with diffraction efficiency higher than 80 % for broadband femtosecond radiation. Special configurations of the acousto-optical delay lines with the increased spectral resolution make it possible to process light pulses in relatively narrow-band CPA systems with glass amplifiers. To solve the problem of spectral phase distortions that are caused by amplitude modulation of ultrasound, we propose a two stage light dispersive delay line for independent processing of spectral phase and spectral magnitude of ultrashort pulses. The first optical unit is aimed for adjusting spectral phase of electromagnetic waves, providing uniform transmission coefficient in the whole optical bandwidth. The second stage works as an optical filter with arbitrarily adjustable transmission function in the given bandwidth. Thus, it becomes possible to eliminate mutual influence of phase and amplitude modulation on spectral shape and spectral phase of light.

In the report, we present the theoretical model of acousto-optical diffraction of ultrashort optical pulses and experimental results of pulse shaping by means of original designed and fabricated light dispersive delay lines. Theoretical simulation of diffraction with high efficiency reveals transformation of pulse shape and broadening of transmission function that are caused by group delay influence on wave coupling during diffraction. The performed experiments showed high-performance operation of the developed acousto-optical dispersive delay lines in different CPA and OPCPA ultrafast laser systems.

8429-26, Session 6

Design of a novel multicore optical fibre for imaging and beam delivery in endoscopy

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With the ever-increasing prevalence of minimally invasive procedures (MIP) in the medical world, the designing of endoscopes, essential in MIP, becomes more and more challenging. Since the continuous and ubiquitous need for miniaturization is starting to outmatch the possibilities offered by the combination of conventional fibre optics and micro-optics, novel approaches are necessary in order to ensure the advancement of endoscopy and consequently of MIP.

In conventional fibre bundles the phase-relation between cores is not conserved during the propagation of an electrical field and as such extra micro-optics at the distal end are necessary in order to be able to focus or scan the exiting light or achieve a certain field of view (FOV). In this paper we analyze the requirements and constraints for a multi-core optical fibre (MOF) which conserves the phase relationship between the cores. With such a phase conserving MOF, focusing and scanning light at the distal end could be done by shaping the wavefront through adaptive optics before coupling the light into the fibre therefore making extra micro-optics superfluous.

Using numerical and mode solving simulations we investigate the relationship between the size, the period and the numerical aperture of the cores on the one hand and the focal point and field of view on the other hand. We show that there is a non-circumventable trade-off between intercore crosstalk and the FOV. In addition, we determine the effects on the focusing ability and on the FOV of deviations of core size and period, due to fabrication errors. Using this knowledge, we propose two designs for the phase conserving MOF. The first design allows for focusing and scanning the exiting light but is sensitive to deviations in core size and separation. The second design is less sensitive to fabrication errors but can only focus and not sweep.

8429-27, Session 6

A multilayer Monte Carlo method with free phase function choice

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This paper presents an adaptation of the widely accepted Monte Carlo method for Multi-Layered media (MCML). While the analytical expression of the Henyey-Greenstein phase function, implemented in the original MCML code, is the most commonly used phase function for biological tissues, it has some important drawbacks. Through the use of this analytical expression, a distribution for the cosine of the deflection angle is defined instead of defining the distribution for the deflection angle itself. This causes a bias in the phase function. This can be clearly demonstrated when generating an isotropic scattering phase function, which results in a uniform distribution of cos(θ). This distribution is no longer uniform when expressing it as a function of θ, since the cosine function is nonlinear. Moreover, this analytical expression with one anisotropy factor g often only gives a rough approximation of the real phase function of the tissue. A more accurate description becomes especially relevant when short source-detector distances are considered.

To overcome these limitations the MCML code has been adapted to accept a non-parametric phase function for each layer, which has been pre-defined and stored as a look-up table. This can either be (1) a Henyey-Greenstein phase function, (2) a modified Henyey-Greenstein phase function, (3) a phase function generated from the Mie theory, or (4) an alternatively defined phase function.

This code was validated by comparing the simulation results obtained with this code in combination with a non-parametric Henyey-Greenstein phase function to those obtained with the MCML code.

The novelty of the developed program lies in the flexibility to generate several types of phase functions and to apply these in multi-layer Monte Carlo simulations without reducing the computational performance.

8429-28, Session 6

A flexible tool for simulating the bulk optical properties of polydisperse suspensions of spherical particles in an absorbing host medium

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Photons travelling through a medium can affect or can be affected by the medium. In medical surgery for instance, laser beams are used for cutting, coagulating and welding tissues and biomaterials. Information on how the light propagates through the treated tissue is crucial for selecting the proper laser, beam power, spot size, and irradiation time. On the other hand, in imaging and spectroscopic analysis, the medium is characterized by measuring transmitted and/or reflected photons. The optimal design of such sensor and the models to be used are, however, depending on the interaction between the light and the medium. Therefore, the characterization of light propagation through all kinds of materials is of major interest for many research areas, including atmospherical science, biomedical optics, food science and many more.

To simulate the light propagation through a diffuse medium, the radiative transfer equation (RTE) needs to be solved by either Monte Carlo simulations, Adding Doubling, Diffusion theory or Kubelka-Munk theory. The parameters used in the RTE are the medium's bulk optical properties (absorption coefficient [μa], a scattering coefficient [μs] and a phase function [p(θ)]) describing the probability of a photon being absorbed, scattered and its scattering direction. Previously, those properties were derived from simulations based on Mie-Theory where the medium is approximated by a monodisperse spherical particulated system in vacuum. In practice however, the host medium is (strongly) absorbing and the particles are polydisperse.

In this study, a tool was developed to calculate the bulk optical properties for systems consisting of an absorbing medium and polydisperse spherical particles that can scatter and/or absorb. The developed tool is based on the Mie-theory for monodisperse-spherical absorbing and scattering particles in vacuum. First, the original Mie-theory was expanded to also include physical (real part of refractive index) and chemical (aborption imaginary part of refractive index) information of the host medium. Secondly, the polydispersity of the spherical particles was taken into account. Since particle size distributions (PSD) are typically continuous distributions and Mie-scattering properties can only be calculated for a monodisperse system, the PSD is fractionated and Mie-scattering properties were calculated for each fraction. These Mie-scattering properties are then combined with the weight for each fraction to derive bulk optical properties. As the number of fractions is unknown and needs to be optimized for each calculation, the developed tool keeps on fractionating until the desired values (μa, μs and p(θ)) converge to stable values. During this fractionating process information from the previous fractionating loops is used to minimize the calculation time. This flexible tool allows simulation of the bulk optical properties for a wide range of wavelengths, particle volume fractions, complex refractive indices of particles and medium and PSD's such as normal, lognormal, gamma, bimodal and custom defined PSD's.

This code was successfully validated for the case of a lognormal PSD of scattering spheres in vacuum by comparing the simulated values to those reported in literature (Mishchenko et al., 2002).

The main novelties of the developed program are the extension of Mie-theory simulations to the case of polydisperse scattering particles in absorbing media and the automatic optimization of the number of PSD fractions needed to converge.

SPIE Photonics Europe

8429-29, Session 6

Two-dimensional analysis of generalized grating imaging in the Talbot-Lau arrangement

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The Talbot-Lau arrangement is an optical system using two gratings of different pitches. The gratings are placed parallel with some distance separated. By illuminating them with a broad incoherent source, we obtain high contrast grating images formed on the planes at the positions determined by the pitches. The phenomenon is called generalized grating imaging. When the pitch of the grating image is smaller than the resolution of the image sensor, the third grating is placed on the grating image plane in order to broaden the pitch by the moiré effect. It is used as the shearing interferometers for light, X-ray, and matter wave. It also used in pattern projection profilometer where two-dimensional hexagonal gratings are used.

There are many analyses on the Talbot-Lau arrangement. However, almost all of them are related to one-dimensional gratings. This paper presents a rigorous analysis on the phenomenon with two-dimensional gratings using wave optics.

A light wave from a broad incoherent source is diffracted by the first two-dimensional grating. The diffracted wave is again diffracted by the second grating, whose lattice system and orientation are the same as the first but its pitch is different. Intensity distribution on a plane parallel to the gratings is expressed as a function of many parameters including the breadth of the light source, the pitches and the positions of the gratings, their unit lattice cell parameters and the position of the observation plane. Contrasts on the observation plane are defined in two different ways. They are calculated based on the intensity distribution.

The analytical result was applied to hexagonal gratings and contrasts were calculated by numerical calculation. Some experiments were made for a Talbot-Lau arrangement with gratings of special parameters with a LED light source. The grating image was detected by an image sensor and contrasts were measured. Experimental results agreed with the numerical calculations. The analysis can be used to design a Talbot-Lau arrangement with two-dimensional gratings in broad fields including light and X-ray.

8429-30, Session 6

Fast computation of the conical response of subwavelength metallic structures using the B-spline modal method

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Structuration at the wavelength scale opens the way to the conception and realization of highly compact optical devices. For this, there is a need for fast computation of the light behavior in such nanostructures, including at oblique incidence, since the numerical aperture remains an important issue in optical components.

To this day, several methods have been specifically developed for 1D-layered metallic gratings. We highlight the B-Spline Modal Method (BMM) [1], based on the resolution of Maxwell and constitutive equations using a B-Spline approximation of the field in each layer. This method enables the use of non-uniform meshes, which is a huge advantage for simulating gratings in which the nanostructurations are much smaller than the period. A more important asset is that we obtain an eigenvalue equation of sparse matrices, which allows us to increase the calculation speed by solving the problem with only a few eigenmodes [2], even for complex systems (e.g. gratings with a high density of slits, or systems based on the coupling of neighbouring slits or dips).

Here, we develop a model for the design and analysis of nanostructured devices at oblique incidence, in which the optical responses of the TE and TM modes are calculated separately before being recombined. We show a good correspondence between the numerical results and the experimental data for various prototypes in the infrared spectral range.

References

[1] P. Bouchon, F. Pardo, R. Haïdar and J.-L. Pelouard, J. Opt. Soc. Am. A 27, 696-702 (2010)

[2] P. Bouchon, F. Pardo, R. Haïdar, G. Vincent, and J.-L. Pelouard, Opt. Lett. 35, 3222-3224 (2010)

8429-31, Session 7

Precise control of dispersion flatness in silicon nitride waveguides by cladding refractive index engineering

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Strategies for flattening the chromatic dispersion in silicon nitride waveguides with silica cladding are numerically investigated. By modifying the transversal dimensions of the silicon nitride core and by adding several cladding layers with appropriate refractive indexes and thicknesses, we are able to demonstrate dispersion flattening over large spectral bandwidths in the near infrared. We analyze several cladding refractive index profiles that could be realistically fabricated by doping the silica with boron, phosphorus or germanium oxides and with feasible atomic concentrations.

We show that cladding engineering allow for much more dispersion control (and flattening) if compared with waveguides where only the core transversal dimensions are optimized. For the latter case it is demonstrated that while the zero dispersion wavelength can be shifted to a great extent, the effect of the cross-section adjustment in the flatness is very limited. In sharp contrast, by adding two silica doped cladding layers with 0.4microns thickness and increased refractive index values, the dispersion ripple can be reduced by a factor of two. By further adding two more layers of the same thickness and by adjusting their refractive indexes it is possible to have nearly constant chromatic dispersion (only +/- 2 ps/nm-km variation) over the spectral region from 1.63 to 1.97microns. In the calculations, the average width and height of the Si_3N_4 core are 2000nm and 730nm, respectively. Dimensions were adjusted around those values and trapezoidal cross-sections were also considered. Furthermore, the change in the silica refractive index due to dopants we analyze here is from 0.5 to 5%. In our optimization procedure, the appropriate transversal dimensions were defined to ensure that most of the light injected would propagate in the fundamental mode.

Our findings on flattening the Si_3N_4 chromatic dispersion might open new avenues for nonlinear applications such as frequency conversion and optical frequency comb generation.

8429-32, Session 7

Self-trapping waveguiding structures in nonlinear photorefractive media based on Plexiglas with phenanthrenequinone molecules

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We present theoretical and experimental investigations of the light beam self-trapping in a photorefractive medium based on Plexiglas (polymethylmethacrylate, PMMA) with photosensitive phenanthrenequinone (PQ)-molecules. It has been shown that self-

trapping of a laser beam is generated due to the self-interaction of the propagating light wave under the conditions of the well balanced concurrence of the effects of light diffraction and nonlinear focusing. A new method for controlling of the waveguide cross-section by changing the ratio of the two competing mechanisms of the nonlinear refractive-index variation (namely the formation of the photoproducts and the heating of the medium while varying the power of the light beam) is proposed.

The recording of self-trapping structures implemented in PQ-PMMA layers has been performed under the action of the laser sources in blue-green wavelength range with an average input power of several mW. It is shown that the photoattachment of the PQ-molecules to the polymeric chains and formation of the photoproduct plays the decisive role in the light-induced increase of the refractive index. Besides, the formation of the waveguide is strongly influenced by heating of the medium, which results in an additional thermal defocusing of the light beam.

It has been established that the parameters of the waveguide (cross-section and its length) are strongly dependent on the wavelength and power of the laser radiation, as well as on the PQ-molecules concentration. For example, the waveguiding structures with the diameter of 100 μm were recorded in the samples with high PQ-concentration (up to 4 mol.%) on the wavelength of 514.5 nm. Reducing the dye-concentration of the order required the shift to the blue wavelength range (405 nm). The dependence of the waveguide parameters and the optimal laser wavelength on the concentration of PQ-molecules is substantiated by the numerical modeling including 3D-model of the light self-trapping.

8429-33, Session 7

Speckle: two new metrology techniques

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Speckle fields are formed when quasi-monochromatic light is scattered by an optically rough surface. These fields are usually described by reference to their first and second order statistical properties. In this paper we review and extend some of these fundamental properties and propose a novel technique for estimating the refractive index of a smooth sample. Theoretical and experimental results are presented. Separately, we also report on a preliminary experiment to determine some characteristics of speckle fields formed in free space by a rotating compound diffuser. Some initial measurements are made where we examine how the speckle intensity pattern in the output plane changes as a function of the relative rotation angle.

8429-34, Session 7

Generation of arbitrary spatially variant polarized fields using computer generated holograms

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Recently, the development of optical setups capable of generating beams with arbitrary polarization have attracted the interest of several research groups (see, for instance, [1-2] and references therein). One possible way to implement such devices is by taking advantage of the properties of liquid crystal spatial light modulators (LCSLM), which act as optical phase retarders controlled by computer. In this communication we present the design of an alternative experimental setup for the generation of light beams with arbitrary spatially-variant polarization distribution.

The objective is to develop a flexible optical device capable of dynamically encode any elliptical polarization state in each point of the wavefront. Our approach is based on a Mach-Zehnder setup combined with a translucent LCSLM in each path of the interferometer. The transverse beam components of the incident light beam are processed independently, and modified by means of their respective LCSLM displaying a specifically tailored computer generated phase holograms [3].

The system has been analyzed numerically and some experimental results are provided.

[1] C. Maurer, A. Jesacher, S. Fürhapter, S. Bernet and M. Ritsch-Marte, Tailoring of arbitrary optical vector beams, New Journal of Physics 9, 78 (2007)

[2] Hui-Tian Wang, Xi-Lin Wang, Yongnan Li, Jing Chen, Cheng-Shan Guo, and Jianping Ding, A new type of vector fields with hybrid states of polarization, Opt. Express 18, 10786-10795 (2010).

[3] V. Arrizón, L. A. González, R. Ponce, and A. Serrano-Heredia, Computer-generated holograms with optimum bandwidths obtained with twisted-nematic liquid-crystal displays, Appl. Opt. 44, 1625-1634 (2005).

8429-35, Session 8

Necessary boundary conditions for the transfer function of a feasible optical thin film filter

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In the SPIE article “Exact synthesis of dielectric thin film filters” by A. R.-Schwarzweller and N. Fruehauf an exact synthesis algorithm for dielectric thin film filters with uniform optical phase thickness was presented. This algorithm computes at least one thin film stack which realizes a given filter transfer function. The validity of the synthesized filters is guaranteed by a set of necessary and sufficient conditions the transfer function has to fulfill. However this set of conditions only guarantees strictly positive refractive index values for all layers of each thin film stack. For technological feasibility strictly positive refractive indices are insufficient since only values in a certain range can be fabricated as a thin film layer. This article describes a way how an additional necessary condition for the filter transfer function can be deduced from given technological restrictions concerning the refractive index values as stated above. These technological restrictions are called boundary conditions in the following and are taken as starting point in our derivation. The boundary conditions are given for each layer separately as simply connected compact refractive index intervals which are determined by an upper and lower bound. State of the art thin film deposition systems make it possible to deposit films with an arbitrary refractive index confined within a certain interval.

The essential part of the thin film filter transfer function can be stated as a polynomial. The zero locations in the complex plane of this polynomial determine the filter characteristic. In a first step restrictions on the coefficients of the transfer function polynomial are deduced from the given boundary conditions. These restrictions can also be stated as connected compact intervals. A polynomial which coefficients are intervals rather than fixed numbers is called an interval polynomial and several analytical and numerical methods exist to calculate the real and complex zeros of such a polynomial. In the second step the restrictions on the coefficients are translated into restrictions on the possible zero locations of the polynomial. The zero location restrictions are therefore necessary

that at least one filter stack exists which fulfills the given boundary conditions. Analytical and numerical methods to calculate these restrictions are presented together with a simple example. Since the boundary conditions are only determined by the used fabrication process the presented additional restriction for the location of the zeros has to be calculated only once when a new process is installed.

8429-36, Session 8

B-CALM: an open-source GPU-based 3D-FDTD simulator with multipole dispersion for plasmonics

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Finite-Difference Time-Domain (FDTD) simulation is a widespread technique for electromagnetic calculations. For many problems in nanophotonics three dimensional full-field simulations are required. When applying optimization schemes that require a full-field solution at each iteration step, such as genetic algorithms or adjoint optimization methods, the possibility to find a solution is often limited by the speed of the full-field simulator. Also FDTD simulations are often restricted by the available computational power. While the use of Graphical Processing Units (GPUs) to accelerate FDTD simulation have been reported before, the results have been, to our knowledge, so far limited to the implementation of flat or single-pole Drude dispersion material models in the microwave regime. At optical frequencies, the permittivity of materials can have more intricate features, which requires including multiple resonances to obtain an accurate material model. Moreover, to our knowledge, no GPU-enabled FDTD simulator has been shared with the scientific community under an open source license. In this paper, we present an open-source GPU-based FDTD simulator called B-CALM (Belgium-California Light Machine) that implements an algorithm to simulate multi-pole Drude-Lorentz materials and minimize thread divergence, enabling fast simulations of complex materials. Also, the technique presented to map the multi-pole Drude-Lorentz model on GPUs could easily be used for the implementation of complex non-linear materials. As an example, we use B-CALM to simulate the absorption cross-section of a gold nanosphere and compare the results with Mie theory. We find that a multi-pole Drude-Lorentz model significantly improves numerical accuracy and an overall 30X speedup compared to Meep, a widely spread CPU-based FDTD simulator.

8429-37, Session 8

Tuning localized plasmon resonance peaks in golden nanoparticle arrays

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We used Fourier modal method to numerically calculate the absorption spectra of various 2D periodic gold particle arrays. The fundamental gold particle was chosen to be 20 nm thick circular disc, and initially with a diameter of 50 nm. Circular particles were an interesting starting point to have identical per-particle response for any polarization angle and thus any differences in the results between cases would only be caused by the array of particles.

The first structure we calculated spectrum for had 50 nm diameter for the gold particles which were set in an array with 200 nm period in both x and y directions. For substrate material we chose fused silica. The absorbance spectrum calculated for thist structure showed clear, although rather weak, rise in absorbance around wavelength of 580 nm. If we reduced the period to 100 nm on each direction, the peak absorption wavelength was still 580 nm, but the absorption rose from previous 10% to around 40% at the peak. Naturally absorption was increased on all calculated wavelengths since the density of gold particles was higher.

When we changed the structure so that every second gold particle has a diameter of 100 nm instead of 50 nm, in a checkerboard fashion, and had period 200 nm, the resonance peak wavelength shifted to 650 nm and the effect was also considerably stronger with absorbance being about 50% at maximum. Overall absorption level was lower than in the previously mentioned 100 nm period case, but peak absorbance was higher. The most probable explanation for this effect is change in localized surface plasmon excitation either due to larger effective period giving new diffraction orders or because of the different particle sizes.

In order to test this, we also calculated case where all the nanoparticles had 100 nm diameter, reducing the effective period back to 200 nm. The spectrum for this case was very much similar to the previous one, with just the overall absorption level being higher due to higher concentration of gold. This shows that the shift in optimal localized surface plasmon excitation wavelength was caused by adjusting the gold particle diameters.

Based on these numerical results alone we can already conclude that it is possible to tune the plasmon resonance wavelength for gold particle arrays by simply adjusting the particle sizes. As for adjusting the strength of the absorption, some compromises need to be made to choose the optimal distance between the particles. While decreasing the distance does clearly promote the effect, it will cause other absorption effects of the metal to increase as well.

8429-38, Session 8

Dielectric structured components for giant field enhancement

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Field amplification within optical devices is a classical challenge that has found numerous applications for bio-sensors and low laser threshold, micro-cavities... Photonic cristals are most often used in guided-wave optics but thin films play the key role in free space optics. Most devices involve thin metallic layers so-called plasmonic devices, due to high stability, low cost and standard technology.

Enhancement of the stationary field is well-known in narrow-band filters. With transparent Fabry-Perot devices at normal incidence with p = 2(q+1) layers in each mirror, it is proportional to a power of the index ratio beta = nH/nL, that is:

SI = |Emax/E0|² ≈ beta^{2(p-2)}

with nH and nL the refractive indices of high and low index materials. However with such devices the field remains confined within the spacer layer and provides weak sensitivity to the surrounding media. For this reason total reflection is preferred, due an evanescent field in the substrate where contamination or pollution can be directly detected. For an efficient sensitivity, the field should the higher in this medium, which justifies efforts to optimize the design.

In this paper we show how multi-dielectric structures allow to reach optimized amplification, that is, a field enhancement much higher than that of plasmonic devices. The gain on the magnitude order is huge but is accompanied by a reduction of stability that we will quantify.

8429-39, Session 9

Wave-optical formation of the intensity distribution and diffraction limit of picture-generating freeform surfaces

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Recent developments in design algorithm enable to design freeform surfaces that generate intensity distributions with middle to high spatial frequency. Such freeform surfaces can generate a picture in a defined plane. In contrast to conventional imaging, the light modulation is done by a ray-optical redistribution of the incident light comparable to incoherent beam shaping.

Such picture-generating freeform surfaces have various advantages.

As only one single optical element is needed to generate the intensity distribution, very compact optical systems can be designed. Additionally, they are highly energy efficient, as nearly 100% of the incident light is directed into the image plane. In case of a freeform mirror, the system is wavelength independent, which offers the possibility for applications in UV or IR spectral range, as well as the polychromatic projection without any chromatic aberration.

As no classical imaging is performed, conventional evaluation criteria concerning the resolution of this picture-generating system like e.g. the Rayleigh criterion cannot be applied. In order to simulate diffraction effects in the picture plane, the wave-optical propagation has to be simulated. However, depending on the geometrical arrangement of such systems, the surface modulation of the freeform can be up to several millimeters. This leads to a violation of the thin element approximation and to significant sampling problems using conventional propagation algorithms. Therefore we used a propagation method based on the Huygens-Fresnel principle.

The physical formation of the intensity distribution of a picture-generating freeform system was simulated and the diffraction limit evaluated. We will show that such systems have a significantly lower resolution than conventional imaging systems. However, they are very well suited for middle- and low-resolution applications.

8429-40, Session 9

Laser beam shaping by conical refraction in biaxial crystals

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When a collimated light beam propagates along one of the optical axes of a biaxial crystal, the beam spreads inside the crystal into a hollow slanted cone and exits the crystal as a hollow light cylinder. It is shown that this effect of conical refraction possesses an extreme versatility in manipulations with light beam profiles, when various beam configurations like Bessel-Gauss, Hermite-Gauss, Laguerre-Gauss, and others can be produced from a lowest-order Gaussian beam by simple manipulations with beam focusing and polarization. Further transformations of the beam profile and formation of more complex light patterns can be obtained in a cascaded scheme, when the beam is passed consecutively through two or more biaxial crystals. These observations demonstrate the unique properties of the effect in manipulations with the amplitude, phase, and polarization of light beams. All the observed transformations of beam profiles were analyzed in a paraxial approximation and good agreement with experiment was obtained.

A biaxial crystal can be used in combination with another nonlinear crystal. In this case, the conical refraction of an intense laser beam in the first crystal is accompanied by a nonlinear optical process driven by the transformed laser beam in the second nonlinear crystal. The results of such a cascaded transformation of laser beams with nonlinear frequency doubling will be presented.

8429-41, Session 9

A new fly's eye homogenizer for single mode laser diodes

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A new fly's eye homogenizer that enables one to achieve uniform flat-top intensity distribution from single-mode laser diodes is presented. In order to achieve a flat-top illumination, fly's eye homogenizers have conventionally been used. However the usage of fly's eye systems has been technically limited to poorly-coherent light sources such as excimer lasers and LEDs. It is well known that laser diodes of low M^2, in particular single mode laser diodes do not work well in a fly's eye homogenizer because they create a strong interference pattern on the image plane when all the beamlets from the fly's eye lens array are overlapped. This is caused by their high spatial and temporal coherence.

In this report, we present a novel fly's eye homogenizer for a single mode laser diode that destroys the coherence of adjacent beamlets, and with which we are the first to solve the above mentioned problem and obtain a highly uniform line illumination. The proposed fly's eye homogenizer includes a method of controlling both the spatial coherence and the temporal coherence of a laser diode by simultaneously applying optical and electronic disturbances. To reduce the temporal coherence, the injection current is driven at 315MHz pulse, which results in a wider spectrum bandwidth. To eliminate the spatial coherence, we introduce a staircase element placed between a pair of fly's eye lens arrays. The step height of the staircase element is designed such that each step creates a different optical path length for each beamlet and the resultant optical path differences give zero visibility for the high frequency pulsed mode. We have achieved an excellent flat-top profile with a local non-uniformity of 5% compared to the conventional case with 98% using a 250 mW UV-blue single mode laser diode.

8429-42, Session 9

Explication of diffraction lights on an optical imaging system by Fraunhofer diffraction perspective

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Low height camera modules are demanded for such applications as cellular phones and vehicles. In optical lens design, it has widely been recognized that a trade-off exists between reducing the number of lenses and camera resolution. Using diffraction gratings has been proposed to improve optical performance. Diffraction gratings, which have a peculiar inverse dispersion in the wavelength that exhibits the efficacy of correction for chromatic aberration, reduce the number of lens and simultaneously maintain optical resolution.

Unfortunately, general diffraction gratings generate unnecessary order diffraction lights such as 2nd or 0th orders, which are caused by the wavelength dependence of the diffraction efficiency, and deteriorate image quality. To solve this problem, we developed new diffraction elements called "White Grating Lens," which consist of a thin nanocomposite resin that covers a grating lens. The nanocomposite resin is adjusted to realize approximately 100% 1st order diffraction efficiency in the entire range of the visible wavelength.

However, in our recent study, we found that striped diffraction lights, which differ from unnecessary order diffraction lights, are generated under intense light sources even on our proposed White Grating Lens. These striped diffraction lights also impede the formation of high-resolution images. With further examination, we elucidated the mechanism of the generation of these striped diffraction lights that can be explained by the theory of Fraunhofer diffraction. Each zone, which was separated by the grating steps of the diffraction grating, resembles narrow slits and causes Fraunhofer diffraction. We found that the striped intervals of the diffraction lights in the theory correspond to those in our experiment. In this paper, we suggest new structures of diffraction gratings that can decrease the striped diffraction lights.

8429-43, Session 9

Design rules for IR microcameras based on a single diffractive optical element

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Conventional infrared cameras are composed by an optical bloc (warm lenses outside a dewar) and a detection bloc (a cooled focal plane array inside the dewar). An important effort is done to reduce the size and the weight of such cameras. It has been demonstrated that an optical function can be added to the dewar by integrating an optical device. The advantage of such a design is to get a complete camera which size is reduced to the size of a dewar. The drawback is that the inserted optical device represents an additional mass that must be cooled down. To give an optical function to the dewar thanks to a light component, we are

focusing on Diffractive Optical Elements (DOE) which are thinner and lighter compared to lenses. An infrared pinhole camera has already been made to prove the relevance of this approach. We now try to improve this camera by replacing the pinhole with diffractive optics that collect and concentrate more light on the detector. Two kinds of DOE are under investigation: difractive axicons and Continuously Self-Imaging Gratings (CSIG). The diffractive axicon is a DOE that generates a focal line along the propagation axis, giving a very narrow Point Spread Function (PSF) in the transverse plane and a very long depth of focus to the camera. The CSIG is the periodic counterpart of the diffractive axicon since it produces a periodic array of narrow focal lines. For convenience, it is easier to make a binary approximation of these components. Therefore, in this paper, we will study the effect of binarization of these gratings. Their Modulation Transfert Functions (MTF) will be compared as well as their radiometric performances. In conclusion, experimental results will be presented to show that it is possible to create a small and compact infrared camera with a thin and lightweight DOE.

8429-59, Poster Session

Advanced multi-plane phase retrieval using Graphic Processing Unit: augmented Lagrangian technique with sparse regularization

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No abstract available

8429-60, Poster Session

Formulation of adaptive Adam-Bashforth method for solving ordinary differential equations: modeling of highly doped waveguide amplifiers

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Accurate modeling of dynamic optical interactions such as saturation and re-absorption in highly doped waveguide amplifiers requires solving a stiff system of ordinary differential equations (ODEs). Traditional ODE solvers including Range-Kutta methods are computationally ill-suited for such applications. In this paper, we derive and apply predictor - corrector adaptive Adam-Bashforth scheme for modeling the population dynamics in Erbium - Doped Fiber Amplifiers (EDFA). Predictor and corrector equations for adaptive Adam-Bashforth have been derived by using Lagrange polynomial as basis rather than the Newton polynomials used in constant step-size Adam-Bashforth scheme. Convergence and stability analysis conducted on the scheme, shows that the method has similar characteristics as that of constant step-size conventional Adam-Bashforth methods for small changes in step sizes. Solutions have been validated by re-generating the absorption and emission coefficients for doped fibers with two different doping concentrations, which is found to match with the manufacturer data-sheet. This method is compared with method like Euler and the optimum order of predictor and corrector is estimated. The result show that this modified form of the scheme results in 75% reduction in step-size to maintain an relative accuracy level of 10^{-3} as compared to adaptive Euler method.

Finally, different orders were compared by using ratio of step-size and number of operations per step as a metric for Figure of Merit (FOM). FOM analysis shows that use of higher order methods are not efficient in reducing the number of steps required to obtain accurate results. It is found that the scheme with both second order predictor and corrector is computationally most efficient. However, in terms of accuracy second order predictor and third order corrector is more suitable with only a marginal degradation of FOM.

In summary, our work shows that such a method is able to adapt to dynamic interactions in the amplifier and provide accurate results in linear, saturation as well as re-absorption regimes. Such a method can be extended to solve more complex optical interactions such as nonlinear Schrodinger wave equation.

8429-61, Poster Session

Method of optical image coding by time integration

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Method of optical image coding by time integration is proposed. Coding in proposed method is accomplished by shifting object image over photosensor area of digital camera during registration. It results in optically calculated convolution of original image with shifts trajectory. As opposed to optical coding methods based on the use of diffractive optical elements the described coding method is feasible for implementation in totally incoherent light. The method was preliminary tested by using LC monitor for image displaying and shifting. Shifting of object image is realized by displaying video consisting of frames with image to be encoded at different locations on screen of LC monitor while registering it by camera. Optical encoding and numerical decoding of test images were performed successfully. Also more practical experimental implementation of the method with use of LCOS SLM HoloEye PLUTO VIS was realized. Objects images to be encoded were formed in monochromatic spatially incoherent light. Shifting of object image over camera photosensor area was accomplished by displaying video consisting of frames with blazed gratings on the LCOS SLM. Each blazed grating deflects reflecting from the SLM light at different angle. Results of image optical coding and encoded images numerical restoration are presented. Obtained experimental results are compared with results of numerical modeling. Optical image coding with time integration could be used for accessible quality estimation of optical image coding using diffractive optical elements or as independent optical coding method which can be implemented in incoherent light.

8429-62, Poster Session

Generalized model for beam-path variation induced by spherical mirrors' radial displacements in square ring resonator and its applications in backscattering coupling effect

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Beam-path variation means a change of light propagation in ring resonator, which including not only optical-axis perturbation but also the variation of beam-path length and positions of every point on beam path. Based on the augmented ray matrix approach, a generalized model for beam-path variation induced by spherical mirrors' radial displacements in square ring resonators has been established. The model can be applied to analyze beam-path variation induced by all the possible perturbation sources in various ring resonators. The resonator geometry and the distribution of backscatter sources turned out to be one of the most significant error mechanisms of the laser gyro. As a decisive parameter of threshold of laser gyro, backscattering coupling effect in square ring resonator has been chosen as an example to show its application. Backscattering coupling coefficient r is obtained as a function of mirrors' radial displacements. Delta1x, Delta2x, Delta1y and Delta2y are radial displacements of spherical mirrors P1 and P2 in square ring resonator respectively. To make the optical-axis pass through the center of the diaphragm Delta1x = Delta2x must be satisfied during the alignment procedure. Because the magnetic bias of the ring

laser gyro can be reduced effectively utilizing a novel method in our previous paper, radial displacements of spherical mirrors along the y axis which may induce magnetic bias are out of consideration. Some novel results of backscattering coupling effect have been obtained. The results indicate that radial displacements Delta1x and Delta2x cause bigger beam-path variation than the same value of axial displacements Delta1 and Delta2. r can not be reduced to zero because of the initial machining errors of terminal surfaces of plane mirrors. However, r can be reduced to almost zero when stabilizing frequency of laser gyro by adjusting the radial displacements of spherical mirrors. The lock-in threshold will be decreased several orders of magnitude by a change of the beam path geometry, then the performance of laser gyroscopes will be improved significantly. All those results have been confirmed by related experiments. The analysis of beam path variation in ring resonator can also be applied in adjustment of ring resonator geometry. In this way, combining related experiments, very flexible manipulation of light in ring resonator can be achieved. This generalized model is useful for the cavity design, cavity improvement, and alignment of planar ring resonators. The model is also useful for controlling the shape of laser beams and researching backscattering coupling effect in high precision laser gyroscopes.

8429-63, Poster Session

Extended focal depth imaging using single and double peacock eye phase diffractive elements

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The “peacock eye” phase diffractive element focuses an incident plane wave into a segment of the optical axis although it introduces certain amount of aberration. This paper evaluates the extended depth of focus (EDOF) imaging performance of the peacock eye phase diffractive element and explores some potential applications in ophthalmic optics. Two designs of the element are analyzed: a single peacock eye, which produces one focal segment along the axis, and a double peacock eye, which is a spatially multiplexed element, that produces two focal segments with partial overlapping along the axis. The performances of the peacock eye-based elements are compared with the performance of a multifocal lens in the image space through numerical simulations as well as optical experiments. In all the cases considered, we obtain the point spread function and the image of an extended object. The results are presented and discussed.

8429-64, Poster Session

Modeling the pulsed laser deposition process at the presence of a background gas and finding the optimal growth conditions for optical applications

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In this work, we present our new simulation model for describing the Pulsed Laser Deposition (PLD) process at a microscopic level. In this Monte Carlo model, calculations are made very efficient using the SRIM 2010 code capability to quantum mechanically describe interaction of ablated species with background gas atoms and their subsequent collisions with film atoms. Using this model, growing parameters of interest in PLD, like the thickness profile of the film, the deposition rate, the mean number of produced vacancies in the film, the implantation depth of the ablated ions and the sputtering yield can be calculated to achieve the optimal deposition conditions. Type and pressure of the background gas and target to substrate distance can be effectively chosen by optical PLD practitioners before performing experiments through using this model. Considering the aluminum material as a typical case and simulating its growth in different noble gases at the pressure levels that are mostly used in PLD (between 30-200 mTorr), two different approaches for the growth of optical films can be proposed. In order to obtain thick layers of active laser materials for waveguide or disk laser fabrications, one should use a gas with low atomic mass at lower pressures. However, to grow high quality thin films for coating the optical elements that are used in the construction of laser systems or for various other optical applications, a gas with low atomic mass at higher pressures is recommended. Our model can be used to obtain the first estimates of PLD parameters for the growth of more complex materials in the presence of different gases.

8429-65, Poster Session

A novel assembly method to eliminate unavoidable fabrication distortion angle in square ring resonator

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A novel assembly method to eliminate distortion angle in square ring resonator has been proposed in this article. Due to fabrication errors and inaccuracies introduced in polishing of the terminal surfaces, there exists unavoidable distortion angle in square ring resonators. Even if the distortion angle is very small, there still exists an output magnetic bias which affects the ring laser gyro’s performance. A novel model of ring resanators in which the gain region is divided into two sections has been established. The situations that the uniform or nonuniform magnetic fields exist on both sections and the magnetic field exists on one section only are discussed respectively. When the differences of the reflectivity for ‘s’ and ‘p’ type polarizations of light and the phase shifts of four mirrors are equal and the uniform magnetic fields exist on both sections, the magnetic biases produced in two sections will totally cancel out each other and the output magnetic bias is zero. When the nonuniform magnetic fields exist on both sections or the magnetic field exist on one section only, there exists an output magnetic bias. According to the theoretical calculation, the relationship between the magnetic bias and the distortion angle is linear relation. The theoretical scale factor kt between the magnetic bias and the distortion angle can be obtained. In this novel assembly method, firstly, the magnetic bias is measured after alignment of optical-axis of ring cavity. Then the distortion angle is changed by adjusting the radial displacements of two spherical mirrors oppositely. The magnetic bias is measured again. The experimental scale factor ke between the magnetic bias and the distortion angle can be obtained according to the results of this two measurement. The theoretical scale factor kt is approved to be correct by the experiment. According to the scale factor, the distortion angle can be eliminated by adjusting the radial displacements of two spherical mirrors and the magnetic bias will be reduced effectively. Both those results and method have been confirmed by related experiments. These findings are important to the research on super high precision ring laser gyros.

8429-66, Poster Session

Comparison of simplified theories in the analysis of the diffraction efficiency in surface-relief gratings

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In this work a set of simplified theories for predicting diffraction efficiencies of diffraction phase and triangular gratings are considered. For instance, triangular gratins are promising for applications requiring

antireflection, polarization selection and spreading. The simplified theories applied are the scalar diffraction and the effective medium theories. These theories are used in a wide range of the value Λ/λ and for different angles of incidence. However, when $1 \leq \Lambda/\lambda \leq 10$, the behaviour of the diffraction light is difficult to understand intuitively and the simplified theories are not accurate. In this paper, we used gratings having periods ranging from one to several tens of wavelengths. The effect of surface profile parameters of the gratings in the simplified methods and their accuracy is studied also. The accuracy of these formalisms is compared with both rigorous coupled wave theory and the finite-difference time domain method. These two methods belong to the rigorous electromagnetic vector theories, and are frequently applied to yield exact diffraction performances. Regarding the RCWT, the influence of the number of harmonics considered in the Fourier basis in the accuracy of the model is analyzed for different surface-relief gratings. In all cases the FDTD method is used for validating the results of the rest of theories. The FDTD method permits to visualize the interaction between the electromagnetic fields with the whole structure providing reliable information at real time. The drawbacks related with the spatial and time resolution of the finite-difference methods has been avoided by means of massive parallel implementation based on graphics processing units. Furthermore, analysis of the performance of the parallel method is shown obtaining a severe improvement respect to the classical version of the FDTD method. The non periodical variation of the refractive index is also considered and analyzed by means of the FDTD method obtaining interesting characteristics related with the tunneling of light.

8429-67, Poster Session

Mathematical modeling of optical properties of biological structures, taking into account large-scale inhomogeneities

K. G. Kulikov, St. Petersburg State Polytechnical Univ. (Russian Federation)

In this paper a mathematical model of a plane wave reflection from the layer, which simulates the biological structure of a slowly varying thickness, taking into account the roughness on the condition that characteristic dimensions of the irregularities on the surface is considerably higher than the wavelength. The model allows to vary the magnitude of the irregularities rough surface, the electrical parameters of the investigated biological specimen geometry and establish the relationship between them and biological properties of the simulated tissue.

8429-68, Poster Session

Accounting for small-scale inhomogeneities in the simulation of electrophysical characteristics of an optically thin layer method intracavity laser spectroscopy

K. G. Kulikov, St. Petersburg State Polytechnical Univ. (Russian Federation)

A mathematical model is constructed, which makes it possible to vary the characteristic sizes of roughness, the electrophysical parameters of the biological sample under investigation, and its geometrical characteristics and to establish the relations between these parameters and biological properties of the biological tissue being modeled, as well as to calculate theoretically the absorption spectra of optically thin biological samples placed into the cavity of an optical resonator.

8429-69, Poster Session

Light scattering by dielectric bodies of arbitrary shape with the application to biophysical problem

K. G. Kulikov, St. Petersburg State Polytechnical Univ. (Russian Federation)

The paper developmend mathematical model for prediction of optical properties (refractive index and absorption) of the simulated tissue (epidermis, upper dermis, blood and blood corpuscles), probed with a laser beam for the case in vivo. In this case blood cells are modeled by particles of irregular shape in different sizes, randomly oriented in free space. Within the bounds of the model investigated depending on the optical properties (refractive index and absorption) of the simulated tissue (epidermis, upper dermis, lower dermis, blood and blood corpuscles), and calculated spectra of the absorbed laser power and oxyhemoglobin deoksigemoglobinom blood conditioned to selective absorption emission of mentioned derivatives of hemoglobin.

8429-70, Poster Session

Analysis of the geometry of a holographic memory setup

A. Márquez, E. Fernández, F. J. Martínez-Verdu, S. Gallego, M. F. Ortuño Sanchez, A. Beléndez, I. Pascual, Univ. de Alicante (Spain)

Typically 4-f systems are considered as the basis for holographic memory setups. However, other geometries, such as the convergent correlator, may also be considered. This is a setup widely used in optical processing architectures but not so much explored in holographic data storage systems. It provides some benefits when used in optical processing such as flexibility in the adjustment between Fourier filter dimensions and the Fourier transform of the scene. It also allows a wider freedom in the choice of the optical systems (lenses) used in the setup since it is no longer necessary that their focal lengths match, and the total length of the setup may be shortened. In this paper we make use of Fourier optics techniques to analyze the validity and possible benefits of this setup in its application to holographic memories. We consider the recording and the reconstruction steps. We further consider the use of the system in associative memory retrieval of information. Tolerances of the system to defocusing, and effects produced by finite size of the optical elements, pixel size of the LCD and imperfections in its modulation are considered. Both analytical expressions and simulated results are given.

8429-71, Poster Session

Study of the stability in holographic reflection gratings recorded in PVA/AA-based photopolymer

E. Fernández, R. Fuentes, M. Ortuño Sanchez, A. Beléndez, I. Pascual, Univ. de Alicante (Spain)

In the last decade holography has acquired great importance since devices are being created that can store the information in the entire volume of the material, thereby increasing the storage capacity in comparison with two-dimensional devices that only store the information on the surface. Pioneering companies in this field, such as Bayer MaterialScience and InPhase even came together to create the TapestryTM, the first prototype of holographic optical storage system that is being used by leading companies and is capable of storing from 200 Gbytes to 1.6 Tbytes in a disk of 130 mm in diameter.

The most widely studied branch of holography, which has given rise to a large number of papers, is transmission holography. However, leading companies such as Bayer are beginning to conduct studies aimed at

using reflection holography. In order to obtain more compact systems it would be interesting to design reflection holographic memories to which the current technology for reading CD's and DVD's designed for reflection holograms may be applied.

Reflection holographic gratings are recorded using a symmetric geometry in a PVA/AA photopolymer with different component concentrations in layers about 70 µm thick.

Once the holographic reflection gratings are stored, the transmittance of the grating will be measured versus the readout wavelength using a double-beam spectrophotometer at normal incidence in order to obtain their diffraction efficiency.

The photopolymers are materials that suffer shrinkage and diffusion phenomena, which cause changes in the diffraction efficiency of the gratings or in the spatial period generating a change in the Bragg angle or in the Bragg wavelength where the maximum diffraction efficiency appears.

In this work the changes due to shrinkage in the diffraction efficiency and in the Bragg wavelength as a function of time elapsed since the recording until the moment of analysis of the grating are studied, and some methods of fixing to reduce the changes of these parameters with time will be applied.

8429-72, Poster Session

Holographic optical elements based on edge-lit holograms

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A holographic optical element (HOE) simultaneously accompanied with light guiding and beam shaping function is implemented with edge-lit holograms in this study. This holographic optical element is generated by one spherical reference beam with large incident angle and one plane signal beam with normal incident angle on a polymer-dispersed-liquid-crystal film. The polymer-dispersed-liquid-crystal film consists of 3-acryloxypropyltrimethoxysilane (APTMS, 50.4 wt%), trimethylolpropane triacrylate (TMPTA, 21.6 wt%), photoinitiator (PI, 3 wt%), photosensitizer (PS, 0.1 wt%) and liquid crystal (E7, 25 wt%), and the thickness of the material used in the experiment is 20 µm. In the holographic reconstruction process of the HOE, the wavefronts emitted from the light source will propagate to the HOE and a quasi collimation diffraction beam can be obtained from this device. In addition, the propagation direction of diffracted light can be pre-arranged in the holographic writing process. The edge-lit architecture of the HOE makes it perform high potential in application of compact systems. We demonstrate two applications of edge-lit HOE in this study. One demonstration is the head-mounted display (HMD) system, and the other is an illumination device for display holograms. In demonstration of a HMD system, we located a display panel at the position of the recording spherical reference wave, and we found the HOE diffracted a virtual image locating at infinity successfully. In demonstration of an illumination device, we used a light-emitting-diode (LED) as the original lighting source, and then the HOE transformed the illumination wavefronts from the LED to be a quasi collimation wave. We have successfully used the diffracted quasi collimation wave as the reconstruction beam for a rainbow hologram which diffracted a 3D image.

8429-74, Poster Session

Behaviors of four different photosensitizers in photopolymer material

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For practical holographic applications such as data storage, understanding the behavior of different dyes in the photopolymer is necessary, as they are crucial in determining material behavior. The Non-local Photo-Polymerization Driven Diffusion (NPDD) model has been verified experimentally and provides physical insights into a material's performance and how it might be improved. It thus provides a tool for quantitive comparison of different material compositions predicting their fundamental performance limits. In this paper we estimate the key dye parameters values of the photosensitizers, (i.e., molar absorptivity, ε, quantum efficiency of the reaction, ϕ, recovery rate, kr, and bleaching rate, kb), and the related simulation work has been done as well

8429-76, Poster Session

Optical designs of micro-objectives with use of base elements

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Today the increasing distribution receives a principle of modular construction of optical designs of microobjectives which as from cubes develop of separate base optical components. These components should be universal under the dimensional and aberrational characteristics. The most widespread base elements are single lenses, and also double triple cemented. As base elements can be not only lenses, but also combinations of lenses, their composition. In work theoretical bases of application of base optical elements with beforehand known dimensional and aberrational properties are resulted. The suggested technique is used at calculation of optical systems microobjectives. The theory of aplanatic surfaces is used also in calculation of objectives of big magnifications. However practical results of microobjectives calculation have shown that the nomenclature of base elements can be essentially expanded.

8429-77, Poster Session

Athermalization of catadioptric infrared camera under uniform thermal distribution

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Optical systems are designed, optimized and fabricated under normal enviromental circumistances, 20 degrees and 1 Atm. peresssure. But, there is no guarantee that normal circumistances are stable in all enviroments.

The temperature is changing in any operationa session.It will leade to change in index of refraction for optical componetnts which in result, changes the whole system focal length. A defocus aberration will happen. It is obvious that such effect is harmful for system operational goals.

To avoid such effects,optical designer should aethermalize optical system.In this process, the effect of temperature change on optical components and mechanical parts of the system is studied. Then, by choosing proper optical materials and suitable materials for mechanical parts, the system will be athermalized. It is athermalized, because length increase for one mechanical part, must be neutralized by length decrease for another mechanical part.

In this paper,a ctadioptric infrared camera is used for athermalization process.Using optomechanical format of the system, we know the material of all lenses used in design and dimensions of mounts,holders and other mechanical parts. choosing suitable the material for mounts, the system will be athermalized.

Temperature change is not only changes the material index, but also affects the radiuses of the optical components. Thus, the component characteristics change is also very important and should be considere.

After starting analysis, we cameo conclusion that changing the radiuses and distances between mirrors, has the worst effect on image quality.By results from calculation, we could choose the material for mirrors and the

holder of two mirrors.

Also we concluded that the distance change between lenses is not very effective onimage quality.

By optomechanical analysis, we chose the material for detector holder and the form of the mounts for lens junction to primary mirror.

By this method, the optical system is athermalized for long temperature range from -40 degrees to +60 degrees under uniform thermal distribution.

8429-78, Poster Session

The visible spectrum transmission on multimode interference

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Major reasons for many natural light illumination systems are high capital cost. And there is a lot of cost about the transmission, in traditional are using optical fibers or reflection light pipe. There are expensive manufacture costs of those two elements. Therefore we proposed using the mmi structure to guide the visible spectrum and makes those could be used in long distance transmission and indoor illumination.

People have concerned green energy issues in recent years; Lots of researches focus on natural light illumination system, health lighting system, especially on solar energy applications. Natural light illumination system is divided into three parts, which are part of collection, part of transmission and part of lighting. In the future, natural light guiding systems could be expected to be used in large areas. Therefore, how to collect the convergence of systems efficiently of natural light is an important topic. In this paper proposed we using the mmi propagation method makes the visible spectrum can be guiding in the same waveguide, which we can design width and length let the majority wavelengths output in the same location. The waveguide material is using PMMA to guide and propagation waves. The main reason we choose PMMA be the waveguide material in this paper that PMMA is cost cheaper, made easily and can be recycling used. PMMA can be regarded as a green energy material. We believe in the future the nature light illumination system can be universal access to using in the greater part of indoor illuminations.

The main goal of this paper is to build and design a new light transmission element, which uses the nature light trans and illumination indoor.

8429-79, Poster Session

Analysis of PEA photopolymers at zero spatial frequency limit

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The PEA photopolymer is composed of dipentaerythritol penta/hexa-acrylate as monomer and binder, N-vinyl pirrolidone as crosslinker, ethyl eosin as dye and N-methyl diethanolamine as radical generator. This photopolymer is suitable to work with dispersed liquid crystal molecules in dynamic holographic and diffractive applications. In order to characterize these materials we have analyzed the behaviour of different compositions at zero spatial frequency limit. This method is based on an interferometer that has been successfully applied in the phase-shift versus applied voltage characterization of liquid-crystal displays, in addition to that it has been applied to characterize PVA/AA and PVA/NaAO photopolymers. In PEA case there is no shrinkage since the photopolymer is coverplated. Samples have a glass substrate as the cover plate. In our analysis we have studied the importance of the monomer, crosslinker and crystal liquid molecules concentrations, in the phase shift produced in the layer during photopolymerization process. On the last place we have analyzed the method to obtain the material samples.

8429-80, Poster Session

Gain and refractive index guiding affects on the mode formation in the solid state laser resonators

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In most quasi three-level lasers (e.g., Yb^{3+} doped gain medium), the inherent absorption of the laser in the un-pumped region of the gain medium works equivalently to a soft transverse gain aperture. This aperture guiding effect dominates the transverse mode formation in the laser resonator. In contrast, in the Nd^{3+} based four-level laser, the un-pumped region has very low absorption at the laser wavelength so that the aperture guiding can be neglected. However, the thermal induced refractive index guiding (or called the thermal guiding) and gain guiding effect are found important for the formation of the transverse mode especially for plano cavity with high power and high intensity pumping.

The combined guiding effect has been observed and studied in the microchip lasers. This is because that, the gain medium with high Nd^{3+} ion doping concentration is always used in microchip laser to achieve effective pump absorption, and this can lead significant thermal induced refractive index guiding and gain guiding. The quadratic index profile is always assumed in the gain medium, and the Gaussian gain profile is used in previous works. Meanwhile, these profiles are always assumed constant along the optical axis in the gain medium. These approximations are only worked for microchip lasers. In particular, the high power fiber-coupled diode pumped laser can get high gain as well as large temperature gradient in the gain medium, and the former approximation on the temperature- and gain- distribution is not enough accurate anymore. Therefore, the combined guiding effect in a general diode pumped laser should be investigated. However, the combined guiding effect in a general diode pumped laser but not in microchip laser has not been theoretically investigated in detail.

In this work, the effect of the combined guiding mechanism on the transverse mode formation of an end pumped laser is investigated theoretically. Both the thermal induced refractive index guiding and gain guiding effect are taken into account. The wave equation of the laser field in the gain medium is established with the combined guiding effect considered. The exact temperature distribution but not the quadratic index approximation is calculated numerically, and the actual gain model but not the constant Gaussian gain is used. In addition, transverse mode of the resonator is calculated using the finite difference beam propagation method (FD-BPM) but not the traditional diffraction integral method.

Numerical model consists of three main steps: firstly, pumped distribution inside the crystal is calculated through an analytical function approximation based on exponential absorption law. At second step, with fraction of absorbed power as heat source, temperature distribution inside the crystal is calculated with finite difference method (FDM).

Finally, the cell-train model of a laser resonator is given, and then the nonlinear Schrodinger-type wave equation in the gain medium is derived in which the combined guiding effect is considered. The finite difference beam propagation method is presented to solve the wave equation and lastly, the profiles of the transverse mode is calculated from our wave equation. This computer laser model makes it possible to propose a special cavity design that can correct the optical distortions of arbitrary shape, including the pump induced thermal lensing, stress birefringence, gain medium surface distortion, and the distortions on the surfaces of other optical components in the cavity. Simultaneously this special cavity can select the spatial eigen mode shape that oscillates.

The laser active media is a composite YAG/Nd:YAG/YAG crystal which pump through its end faces by a fiber coupled diodes. Our simulation results show that both combined guiding mechanisms dominate on the laser mode formation in the resonator.

8429-81, Poster Session

Effect of pH all-optical switching with bR films

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Protein Bacteriorhodopsin (bR) is one of the most promising and widely studied biomaterials for photonic applications like optical storage, modulation devices and photosynthetic light energy transduction. In this paper, we present the corresponding experimental results when pH-controlled modifications of bR doped polymeric films are realized in order to apply these systems to all-optical switching processes and technologies.

In this work, the performance of wild type bR processed in polymeric films with different pH was tested in several series of experiments by varying the pump beam (532 nm) period of ON and OFF and analyzing the amplitude contrast and switching time of the probe beam (633 nm). The influence of pH values on contrast ratio and switching time were also discussed and the optimal value was found by defining a new parameter called “switching speed”. As a result, the variation of pH can be used to obtain different time of response and speed of modulation. Concretely, we find that, in function of pH, variations of a magnitude order in contrast ratio and time response can be obtained. So, at the red region of the probe beam, high pH values produce high transmission with flat response in the contrast ratio and a magnitude order variation in switching time. On the other hand, at medium pH values and when high intensities are used, the switching time and contrast ratio are better. Moreover, it is demonstrated that as a function of the wavelength of the probe beam the transmission response curve changes. Absorption response is very important and depends on relaxation time processes of intermediate species which are function of pH values. Therefore, these results bring the possibility for controlling the contrast ratio and the switching time in a specific way which could be useful for different applications.

8429-82, Poster Session

More exact modeling of COIL laser performance

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The Chemical Oxygen-Iodine Laser (COIL) is the shortest wavelength and high-power chemical laser demonstrated. To model the complete COIL lasing interaction, a three-dimensional formulation of the fluid dynamics, species continuity and radiation transport equations is necessary. The computational effort to calculate the flow field over the entire nozzle bank with a grid fine enough to resolve the injection holes is so large as to preclude doing the calculation. The approach to modeling chemical lasers then has been to reduce the complexity of the model to correspond to the available computational capability, adding details as computing power increased. The modeling of lasing in Chemical Oxygen-Iodine Laser (COIL) medium is proposed, which is coupling with the effects induced by transverse injection of secondary gases, non-equilibrium chemical reactions, nozzle tail flow and boundary layer. The coupled steady solutions of the fluid dynamics and optics in a COIL complex three dimensional cavity flow field are obtained following the proposal. The modeling results show that these effects have some influence on the lasing properties. A feasible methodology and a theoretical tool are offered to predict the beam quality for the large scale COIL devices.

8429-44, Session 10

Characterization of holographic digital data page recording in nanoparticle-polymer composite films based on thiol-ene photopolymerization

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We have recently developed a new class of holographic dry photopolymers, the so-called photopolymerizable nanoparticle-polymer composites (NPCs), where inorganic or organic nanoparticles are uniformly dispersed in (meth)acrylate monomers capable of the chain-growth polymerization. The inclusion of nanoparticles increases the saturated refractive index modulation (Δnsat) and the material recording sensitivity (S) that exceed the required minimum values of 0.005 and 500 cm/J, respectively, for holographic data storage (HDS) media. At the same time the mechanical and thermal stability of recorded volume holograms can be improved with inorganic nanoparticles dispersed in NPCs. When they are considered as HDS media, however, their polymerization shrinkage is still larger than 0.5% (the required shrinkage criterion for HDS media) although it can be reduced as low as 1% by nanoparticle dispersion. To reduce shrinkage with NPCs further, we recently proposed the use of thiol-ene photopolymerizations that proceeded via a step-growth radical addition mechanism. We demonstrated that shrinkage reduction as low as 0.4% was possible with Δnsat and S as high as 0.01 and 1615 cm/J, respectively, in the green by using NPCs with silica nanoparticles and the stoichiometric mixture of secondary dithiol and allyl triazine triene. In this work we report on a concentration dependence of an initiator/sensitizer system on Δnsat, S and shrinkage of plane-wave volume holograms recorded in thiol-ene based NPC films at a wavelength of 532 nm. It is found that a decrease in concentrations of the initiator/sensitizer system results in a substantive reduction of light scattering while Δnsat, S and shirinkage are maintained above the required minimum values for HDS media. We also demonstrate shift hologram multiplexing of digital data pages with scheduled recording. It is shown that the symbol error rate and the signal-to-noise ratio of a recorded data page (60 by 60 symbols) with 2-4 modulation coding are 0.009 and 4.2, respectively.

8429-45, Session 10

Computer simulation of Bragg grating formation in holographic polymer-dispersed liquid crystals based on the density functional theory

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Holographic polymer-dispersed liquid crystal (HPDLC) is an electrically switchable Bragg grating consisting of alternative layers of polymer and liquid crystal molecules. It is holographically recorded by the interference of two or more mutually coherent beams. Photopolymerizable monomer and liquid crystal molecules undergo mutual diffusion and phase separation under holographic exposure, followed by nematic ordering of agglomerated liquid crystal molecules (i.e., liquid crystal droplets) in the dark illuminated regions. Because of a large refractive index difference between the formed polymer and liquid crystal high contrast and optically anisotropic Bragg gratings can usually be obtained. Such HPDLCs have been applied to various photonic devices such as tunable optical filters, displays and photonic crystals. So far, several theoretical models have been proposed for the understanding and control of the Bragg grating formation process in HPDLCs. They may be categorized into two qualitatively different types of models: a phenomenological multi-component model and a statistical thermodynamic model. The former assumes single-phase mixture of monomer and liquid crystal molecules before and during the photopolymerization process. Although it explains several macroscopic features of the diffraction properties

of formed Bragg gratings, it cannot properly treat the detailed physical processes including the mutual diffusion and phase separation of polymerizing monomer and liquid crystal molecules. On the other hand, these processes and nematic ordering can be taken into account at the same time by the latter statistical thermodynamic model. The reported statistical thermodynamic model basically relies on the time-dependent Ginzburg-Landau theory with the Flory-Huggins-de Gennes free energy. It is not limited to small density fluctuations unlike the case of Ginzburg-Landau type free energy. Although the polymerization and phase separation processes involve monomer, polymer and liquid crystal in an HPDLC system, however, the reported model simplifies the system as a pseudo two-component system with one component being liquid crystal and the other being polymer and residual monomer.

In this work we report on a computer simulation study of Bragg grating formation in HPDLCs by using a continuous field statistical thermodynamic model based on the density functional theory. The present simulation method can individually treat the space-time evolution of monomer, polymer and liquid crystal densities in the photopolymerization, mutual diffusion and phase separation processes at relatively low computation costs. The mass conservation and the incompressibility condition are taken into account by using the Lagrange multiplier method. In addition, the realistic photopolymerization process can be included in the simulation. The validity of the proposed simulation method is compared with experiments.

8429-46, Session 10

Kinetics of chain transfer agents in photopolymer material

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The Non-local Photo-Polymerization Driven Diffusion (NPDD) model can be used to study the effects of the chain transfer agents (CTA) in photopolymer material. It predicts that the average chain length formed can be controlled chemically using CTAs, and that optimum types and concentrations of CTAs can be identified. The predictions of the NPDD model indicate that a particular type of CTA with a higher rate constant of chain transfer will produce a lower average polymer chain length and therefore a reduction in the non-local response length. An appropriate re-initiation rate (efficiency) is also required in order to retain a high rate of polymerization. By generating shorter polymer chains, (i.e. decreasing the non-local material response parameter,), the spatial frequency response of a photopolymer material, is improved. In this paper we report the results of an extensive experimental and theoretical study during which the chemical composition of a standard polyvinyl alcohol-acrylamide (PVA/AA) material was modified by including several types and concentrations of CTA having different kinetic rate. Significant improvements in material performance are reported.

8429-47, Session 10

Diacetone-acylamide-based new non-toxic holographic photopolymer

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Acrylamide-based photopolymers are fast becoming one of the most popular recording media for different holographic applications. Their high sensitivity, wide dynamic range and self processing nature, together with their low cost of production, make them an excellent candidate for different holographic applications. However acrylamide is classified by the World Health Organisation as a toxic and carcinogenic substance [1]. As holographic technologies are advanced, there will be a need for recording materials which can be produced in bulk with little risk to manufacturers, and which will not be harmful to the environment when disposed of. This is why the development of a non-toxic alternative photopolymer material is crucial, and has attracted attention in recent years.

A new-non toxic photopolymer material has been developed and optimized. The non-toxic material Diacetone Acrylamide is used as the replacement monomer for Acrylamide in the photopolymer composition. The new material has been observed to achieve refractive index modulation values up to 3.3x10-3, and can reach diffraction efficiencies >90%. These values are comparable to those achieved by the known acrylamide-based photopolymer over a range of spatial frequencies [2]. The photopolymer has been characterized for different conditions of recording, such as recording intensity and total exposure.

The effect of additives such as glycerol and silver ions on the holographic recording ability of the new photopolymer has been characterized. Glycerol has been shown to influence the intensity dependence of the maximum refractive index modulation, and also the rate of photobleaching of the photopolymer layer. Initial studies with silver ions suggest possible formation and redistribution of silver nanoparticles on exposure to light.

[1] Health implications of acrylamide in food: report of a joint FAO/WHO consultation, WHO Headquarters, Geneva, Switzerland, 25-27 June, 2002.

[2] T. Babeva, I. Naydenova, D. Mackey, S. Martin and V. Toal, “Two-way diffusion model for short-exposure holographic grating formation in acrylamide-based photopolymer”, Opt. Soc. Am. 27, 197-203 (2010).

8429-48, Session 10

Recent developments in the nonlocal photopolymerization driven diffusion model

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An understanding of the photochemical and photo-physical processes, which occur during photo-polymerization, is of extreme importance when attempting to improve a photopolymer material’s performance for a given application. Recent work carried out on the modeling of photopolymers during- and post-exposure, has led to the development of a tool, which can be used to predict the behavior of a number of photopolymers subject toa range of physical conditions. In this paper, we explore the most recent developments made to the Non-local Photo-polymerization Driven Diffusion model, and illustrate some of the useful trends, which the model predicts and then analyze their implications on photopolymerimprovement.

8429-49, Session 11

Automated 3D detection and classification of Giardia lamblia cysts using digital holographic microscopy with partially coherent source

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Over the past century, monitoring of Giardia lamblia became a matter of concern for all drinking water suppliers worldwide. Indeed, this parasitic flagellated protozoan is responsible for giardiasis, a widespread diarrhoeal disease (200 million symptomatic individuals) that can lead immunocompromised individuals to death. The major difficulty raised by Giardia lamblia’s cyst, its vegetative transmission form, is its ability to survive for long periods in harsh environments, including the chlorine concentrations and treatment duration used traditionally in water disinfection. Currently, there is a need for a reliable, inexpensive, and easy-to-use sensor for the identification and quantification of cysts in the incoming water.

For this purpose, we investigated the use of a digital holographic microscope working with partially coherent spatial illumination that reduces the coherent noise. Digital holography allows one to numerically investigate a volume by refocusing the different plane of depth of

a hologram (by implementing the Kirchhoff-Fresnel equation). This provides the localization of giardia cysts in the three dimensions and quantitative phase contrast imaging which are not possible with classical microscopes. In order to see clearly the internal structure, microscope lenses of 63x are used given a field of view of 115µm x 115µm. A particular micro-channel is designed to analyze a whole volume in a dynamic acquisition.

In this paper, we perform an automated 3D analysis that computes the complex amplitude of each hologram, detects all the particles present in the whole volume given by one hologram and refocuses them if there are out of focus using a refocusing criterion based on the integrated complex amplitude modulus and we obtain the (x,y,z) coordinates of each particle. Then the segmentation of the particles is processed and a set of morphological and textures features characteristic to Giardia lamblia cysts is computed in order to classify each particles in the right classes.

8429-50, Session 11

Off-axis multispectral digital holographic microscope with partially coherent illumination

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Digital holographic microscopy provides refocusing and quantitative phase contrast imaging. Those capabilities open new investigation modes in particular in life and environmental sciences where it becomes possible to analyze dynamical thick sample with transparent objects. To implement digital holographic microscopy, the common way consists of using laser beams that yield high coherence degrees in order to easily record holograms. However, a high coherence illumination beams gives noisy results, specially the intensity distributions. To improve the image quality, optical sources of reduced coherence provide lower noise results. On another hand, the digital holographic microscopy is often implemented with monochromatic sources. This is limiting in numerous applications, as the detection of specific objects, were the spectral information is of importance. In this contribution, we describe the implementation of a digital holographic microscope using several light emitting diodes (LED) of different wavelengths to achieve both the noise reduction and the recording of the spectral information. The implementation allows the off-axis configuration to make possible the one shot holographic recording. The implementation will be described together with experimental demonstrations.

8429-51, Session 11

A new iterative Fourier transform algorithm for optimal design in holographic optical tweezers

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Holographic Optical Tweezers (HOT) is the most powerful and versatile technique to realize multiple trapping using the Computer Generated Holograms (CGH), displayed by a Spatial Light Modulator. Analytical and numerical approaches exist to calculate the CGH phase distribution able to project trapping light intensities inside the sample volume. The best known are based on the iterative Fourier transform algorithm (IFTA) like Gerchberg-Saxton (GS) and Adaptive-Additive (AA), while exists other non-iterative procedures like Random Mask (RM) encoding technique. All these algorithms corrupt the desired pattern of traps, in some cases with the introduction of ghost traps, such as GS and AA, in others with noise as it happens for the RM. In particular, the ghost traps are unwanted trapping sites with an intensity able to trap particles, and its suppression or reduction is an open problem in HOT. We propose a new IFTA capable to suppress ghost traps and noise in HOT, maintaining a high diffraction efficiency in a computational time comparable with the others iterative algorithms, but it is optimized only in the case of few optical traps (up to 4 traps). The process consists in the planning of the suitable ideal target of optical tweezers as input of classical IFTA and we show we are able to design up to 4 real traps, in the field of view imaged by the microscope objective, using an IFTA built on fictitious phasors, located in strategic positions in the Fourier plane. The effectiveness of the proposed algorithm is evaluated both for numerical and optical reconstructions and compared with the techniques mentioned above, i.e. GS, AA and RM.

8429-52, Session 11

A new algorithm for digital holograms denoising based on compressed sensing

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We propose a new denoising algorithm in off-axis digital holography that is based on compressed sensing paradigm. Compressed sensing is a technique for acquiring and reconstructing a signal using the prior knowledge that the signal is sparse. It states that a signal admitting a sparse representation in some basis can be perfectly acquired using a low rate acquisition process that projects the signal onto a small set of vectors incoherent with the sparsity basis. Exploiting this sparseness can lead to a better approximation of their rate distortion function, and provide constructive guidelines for a more efficient and effective data adapted acquisition, compression and denoising algorithms. The aim of our work is to assess a "universal" denoising of digital holograms, i.e. we do not explore prior knowledge of the statistics of the digital holograms. For this purpose, we consider different experimental conditions such as a digital holograms recorded in microscope configuration and lensless configuration. We use the inherent sparsity of the numerical reconstruction of digital holograms in order to optimize the in-focus digital reconstructions. This optimization is based on the reformulation of original compressed sensing optimization problem for noiseless signals recovery, as a denoising procedure. The output of the denoising algorithm is the best estimation of the support of digital holograms reconstruction. In addition, for the lensless recorded holograms, we perform also a display test, by using a Spatial Light Modulator as a projection system. In fact, after a back propagation of the denoised complex field, we compare the denoised holograms with the original ones. In both numerical reconstruction and display test, we compute the improvements of the proposed algorithm using a different coefficients of quality. Finally, we compare the our algorithm with the other well known denoising algorithms in order to establish the advantage of the proposed one.

8429-53, Session 11

Numerical and optical reconstruction of digital off-axis Fresnel holograms

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Setup for recording digital off-axis Fresnel holograms is described. Obtained digital holograms were reconstructed both numerically and optically. Results of optical and numerical reconstructions are compared. Digital off-axis Fresnel holograms with a pixel size 9 um and the number of pixels up to 2048x2048 for the scene depth up to 480 mm at distances 700-1400 mm were recorded. Experimental setup allows to record holograms in both modes of object's illumination: «on transmission» and «on reflection». For hologram numerical reconstruction various methods were implemented in programming environment MATLAB: direct calculation of Fresnel diffraction (DC), Fresnel diffraction calculation

through fractal Fourier transform (FrFT), angular spectrum propagation and others. Under numerical testing it was found that the best quality of reconstructed object image provides the FrFT method. However the DC method yielded the best results for numerical reconstruction of the recorded digital holograms. It seems that the FrFT method is more sensitive to real noises at hologram recording, which leads to a “double vision” of the reconstructed object image. For optical reconstruction the recorded digital holograms were binarized by the threshold and printed on transparency film with a resolution of 100 dots/mm using laser imagesetter. The optically reconstructed images have higher noise level than numerically reconstructed ones. This is primarily because of holograms binarization. Also the digital holograms were optically reconstructed using LCOS SLM HoloEye PLUTO VIS. The resolutions of displayed digital holograms were limited to 1920x1080 (SLM resolution). Quality of reconstructed images is equivalent to the quality of numerically reconstructed images. Real time holographic video of remote volumetric scenes was experimentally demonstrated through combination of the setup for digital holograms recording and the setup with SLM for their optical reconstruction.

8429-54, Session 12

A novel deformable mirror with curvature and tip/tilt control based on the spider actuator concept

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The Smart X-Ray Optics (SXO) project comprises a UK-based consortium developing active/adaptive micro-structured optical arrays (MOAs). MOA devices are designed to focus X-rays using grazing incidence reflection through consecutive aligned arrays of microscopic channels. Adaptability is achieved using a combination of piezoelectric actuators, which bend the edges of the silicon chip, and a spider structure, which forms a series of levers connecting the edges of the chip with the active area at the centre, effectively amplifying the bend radius.

The spider actuation concept, in combination with deep silicon etching stopped before the wafer is etched all the way through its thickness, can also be used to produce deformable mirrors where the curvature and tip/tilt angles of the mirror can be controlled. The dimensions chosen for the device design are 2cm×2cm×100µm with the active area in the centre 2mm×2mm for the silicon layer and 100µm thickness for the actuator layer. Finite Element Analysis (FEA) modelling, carried out for the optimization of the spider MOA device using segmented electrodes in the actuator layer of the device, indicates that deformable mirrors with curvature varying from flat to 5cm ROC and control over the tip/tilt angles of the mirror of +/-3mrad could be achieved using 100 micron thick silicon wafers. This has been verified by the characterisation of test spider structures manufactured using deep silicon etching using both wet and dry etch processes. The wet etched samples, which were be manufactured in a single step using planes in a (110) silicon wafer for both the silicon channels and the spider structure, have been bent to a radius of curvature smaller than 5 cm. The PZT piezoelectric layer has been manufactured using a combination Viscous Plastic Processing Process for the piezoelectric actuators and laser machining for the dimensional control and electrode pattern definition.

This paper evaluates the spider MOA’s concept as a mean to achieve deformable mirrors with controllable ROC and control over the tip/tilt angles. FEA modelling results are compared with obtained characterization data of prototype structures. Finally, manufacturing and integration methods and design characteristics of the device, such its scalability, are also discussed.

8429-55, Session 12

Dynamics of vesicle suspension in shear flow between walls by digital holographic microscopy with a spatially reduced coherent source

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Digital Holographic Microscopy (DHM) is a powerful tool that strongly increases the field of investigation of classical microscopy. It allows to be used as phase contrast microscopy with the additional information of the z position over a whole experimental volume by acquiring a single frame. The use of a spatially reduced coherent source strongly reduces the coherent noise.

Vesicles are close lipid membranes enclosing a sugar-water solution. Those biomimetic deformable objects are good mechanical models of living cells such as Red Blood Cells. We investigate the dynamics of a vesicle suspension in shear flow between walls (with a gap of about 200 µm). When vesicles are placed in a shear flow, they undergo a lift force that pushes them away from the wall until they reach the centre of the channel where the effects of both walls are compensated. On the other hand, hydrodynamical interactions between vesicles and segregation effects tend to push small vesicles away from the centre of the channel. The final distribution is thus a compromise between both effects that structures the distribution and has strong impact on rheology.

DHM with reduced coherence and specific related algorithms (phase compensation, best focus plane determination, segmentation, ...) provide a full description of each object in the experimental volume as a function of their size and shape. Results are provided and illustrate the quantification of the lift force and the hydrodynamical interactions (shear induced diffusion).

8429-56, Session 12

An iterative approach for modeling the interaction of a partial coherent light distribution with an absorbing photosensitive polymer

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The propagation of coherent light through a heterogeneous medium is an often-encountered problem in optics. Analytical solutions, found by solving the appropriate differential equations, usually only exist for simplified and idealized situations limiting their accuracy and applicability. A widely used approach is the Beam Propagation Method in which the electric field is determined by solving the wave equation numerically, making the method time-consuming, a drawback exacerbated by the heterogeneity of the medium. In this work we propose an alternative approach which combines, in an iterative way, optical ray-tracing simulation in the software (ASAP) with numerical simulations in Matlab in order to model the change in light distribution in a medium with anisotropic absorption, exposed to partially coherent light with high irradiance. The medium under study is a photosensitive polymer in which photochemical reactions cause the local absorption to change as a function of the local light fluence. Under continuous illumination, this results in time-varying light distributions throughout the irradiance process. In our model the fluence-absorption interaction is modelled by splitting up each iteration step into two parts. In the first part the optical ray-tracing software determines the new light distribution in the medium using the absorption from the previous iteration step. In the second part, using the new light distribution, the new absorption coefficients are calculated and expressed as a set of polynomials. The evolution of the light distribution and absorption is presented and the change in total transmission is compared with experiments.

8429-57, Session 12

Optimization of the concentration optics of the Martian Airborne Dust Sensor for MetNet Space Mission

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Martian atmosphere contains a significant and rapidly changing load of suspended dust that never drops to zero. The main component of Martian aerosol is micron-sized dust thought to be a product of soil weathering. Although airborne dust plays a key role in Martian climate, the basic physical properties of these aerosols are still poorly known. Mars MetNet Mission is a collaborative project of Finland, Russia and Spain whose scope is to deploy several tens of mini atmospheric stations on the Martian surface. MEIGA-MetNet payload is the Spanish contribution to the initial mission, “Precursor”. The Infrared Laboratory of University Carlos III (LIR-UC3M) is in charge of the design and development of a micro-sensor focused to characterize airborne dust in terms of the particle size distribution. This design must accomplish with a very severe mass budget of 45 g max. and power budget of 1 W max.

The design criterions are obtained from a physical model developed by LIR-UC3M for optimizing IR local (short range) scattering sensing. The model, based on Mie theory, calculates the spectral power density scattered in the infrared 1-5 m spectral region by a certain particle distribution into the sensor’s field of view (FOV) produced by the local particle scattering at distances of some centimeters. Infrared measuring has some advantages, such a good sensitivity to micron-sized particles, and ability to measure during the night and low dependence on surface reflectance. Due to the very low IR signal expected onto the detector, mainly in the calm periods of Martian climate, a compound ellipsoidal concentrator (CEC) embebed into the sensor packaging has been designed and fabricated. The implementation of this element improves in a factor x 100 the incident IR dust scattered power on the detector, maintaining however the hard constrictions in mass and volume of the dust sensor.

8429-58, Session 12

An approach to the design of wide-angle optical systems with special illumination and IFOV requirements

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The article presents the approach to the design of wide-angle optical systems with special illumination and instantaneous field of view (IFOV) requirements.

The unevenness of illumination reduces the dynamic range of the system, which negatively influence on the ability of the system to perform their task. The result illumination on the detector depends among other factors from the changes in IFOV. It is also necessary to consider IFOV in the synthesis of data processing algorithms, as it directly affects to the potential “signal/background” ratio for the case of statistically homogeneous backgrounds.

The article presents the IFOV creation for electro-optical systems (EOS) which works with remote objects. The solution can be used for optical system which field of view greater than 180 degrees.

A numerical-analytical approach that simplifies the design of wide-angle optical systems with special illumination and IFOV requirements is presented. Illumination calculation in optical CAD is based on computationally expensive tracing of large number of rays. The author proposes to write analytical expression for some characteristics which illumination depends on. The rest characteristic are determined numerically in calculation with less computationally expensive operands, the calculation performs not every optimization step. The results of analytical calculation inserts in the merit function of optical CAD optimizer. As a result we reduce the optimizer load, since using less computationally expensive operands. It allows reducing time and resources required to develop a system with the desired characteristics. The calculation of the IFOV is based on the analyzing of the pixel boundaries distortion on the sphere in the image space. The author propose to use in the approach both analytical and calculation results to determine direction for the further optimization.

Additionally there are expressions for IFOV definition in special cases: when the EOS for Earth observation is located on a space vehicle or on an aircraft.

This approach was used in the design of wide angle optical system with special illumination and IFOV requirements and shows its justifiability.

The proposed numerical-analytical approach simplifies the creation and understanding of the requirements for the quality of the optical system, reduces the time and resources required to develop an optical system, and allows creating more efficient EOS.

8430-01, Session 1

Novel interferometric technique for the measurement of vibration and displacement of rotating components

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In microelectronics, vacuum techniques such as turbo molecular pumps have to fulfill the demand of lowest vibrations. The standard measurement technique for this purpose is the laser Doppler vibrometer. However, vibration measurements of fast rotating objects such as vacuum pump shafts are challenging due to the moving speckle pattern.

A novel non-incremental interferometric technique is presented for precise vibration and displacement measurements of high speed rotating objects. Two inclined interference fringe systems are generated in the measurement volume of the laser Doppler velocimeter. Their signal phase difference depends on the axial position and their signal frequency corresponds to the lateral velocity. Thus, simultaneous position and velocity measurements can be accomplished. However, the tilted interference fringe systems result in different speckle patterns and therefore in systematic measurement deviations. Recently, a new optical concept has been developed, which successfully suppresses these deviations. Also at high speed rotating objects a standard deviation of only 110 nm is achieved. The non-incremental interferometric technique has been applied successfully to vacuum pumps, rotating at 48,000 rpm. Substantial vibration evaluations of the rotating shaft have been performed.

8430-02, Session 1

Influence of Fresnel diffraction on numerical propagation and correction of tilted image planes in digital holographic microscopy

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Digital holographic microscopy enables high-resolution inspection of reflective surfaces and technical phase specimen as well as the minimally invasive analysis of living cells from single recorded digital holograms by multi-focus quantitative phase imaging [1,2]. However, in order to achieve a high resolution in quantitative imaging with DHM typically microscope lenses with a high numerical aperture are applied. This results in a low depth of field (DOF) of the optical imaging system. Thus, for example, surfaces and specimens that cannot be imaged in parallel with the hologram recording device are recorded partly defocused.
We explored the compensation of such defocusing effects by partial numerical propagation of the complex wave fields that are retrieved from digitally recorded off-axis holograms by using a spatial filtering based reconstruction algorithm which follows an approach in [3]. The numerical propagation of small wave field parts with low pixel numbers is affected by Fresnel diffraction and aliasing. Thus, in a first step, the influence of these effects was quantified. The resulting parameters were used in an adapted algorithm for numerical refocusing of tilted image planes that considers the DOF of the applied optical imaging system. Results from simulations and experimental investigations show that typical numerical propagation artefacts origin from Fresnel diffraction which efficiently can be suppressed by adaptation of the numerical propagation. The application of the resulting algorithm during the reconstruction of digital holograms of resolution test charts, reflective surfaces and cellular specimens which were acquired with Mach-Zehnder and self interference DHM setups [4] demonstrates that images planes with a tilt of up to 80 degrees to the hologram plane can compensated.

References

[1] B. Kemper, G. von Bally, “Digital holographic microscopy for life cell applications and technical inspection”, Appl. Opt. 47, A52-A61 (2008).

[2] P. Langehanenberg, G. von Bally, B. Kemper, “Autofocussing in Digital Holographic Microscopy”, 3D Res. 2, 01004 (2011).

[3] C. J. Mann, L. F. Yu, C. M. Lo, and M. K. Kim, “High-resolution quantitative phase contrast microscopy by digital holography,” Opt. Express 13, 8693-8698 (2005).

[4] B. Kemper, A. Vollmer, C. Rommel, J. Schnekenburger, G. von Bally, “Simplified approach for quantitative digital holographic quantitative phase contrast imaging of living cells”, J. Biomed. Opt. 16, 026014 (2011).

8430-03, Session 1

Multilevel optical sectioning based on digital holography with a femtosecond frequency comb laser

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Nowadays, thanks to opto-electronic sensors (CCD, CMOS) and to modern computer resources, the processing of holograms can be performed in a very short time. Different methods based on digital holography have been developed for the measurement of the shape of objects having smooth or rough surfaces. Short coherence digital holography may be used as well for 3D contouring. In this case, the interference between the object and reference wave is just observed when their optical path lengths are matched within the coherence length of the laser. The numerical reconstruction of the hologram corresponds to a defined layer and thus allows optical sectioning. In this paper, we demonstrate how short coherence digital holography with a frequency comb laser may be used for multi-level optical sectioning. For that purpose, a lensless Fourier holographic in-line set-up on the basis of an unbalanced Michelson interferometer with a spherical mirror in the reference arm is used. As light source, a 50mw pulsed fiber laser (pulse duration 100 fs) is used for the generation of the frequency comb (centre wavelength 532 nm, comb spacing 5.994 GHz. Therefore, sectioning planes in the object arm with a spacing of 25.00 mm can be generated. For the proof of the principle, cones having a size of few centimetres are applied. The phase is obtained by phase-shifting, and the object shape is obtained by digital reconstructing and processing of a sequence of holograms recorded during stepwise shifting of the small mirror in the reference arm. First experimental results are presented.

8430-04, Session 1

An alternative reconstructing method in color holography based on digital holograms stretching

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Digital color holography was established by Yamaguchi et al, who proposed a phase shifting method for the recording at three wavelengths. Other works by Demoli, Picart and others have led to early studies on fluids, using digital color Fourier holography, structural mechanics, crack investigation in electronic components. In several papers the multi-wavelength analysis is used for compensation of chromatic aberrations and quantitative phase imaging. In these last cases, microstructures, like MEMS, or different type of cells, are recorded at different wavelength in order to quantitatively study their three-dimensional structure. The reconstruction of digital color holograms can be performed using the discrete Fresnel transform or the convolution method with a zero-padding. Other different numerical procedures are based on the control of the size of digital holograms, the pixel resolution, and the image scaling. We propose an alternative reconstructing strategy based on the stretching techniques that was recently developed by Paturzo et al. With a simple affine transformation on the Fresnel reconstructions and correlation-matching procedure, we are able to manage the digital color reconstructions of the same object in order to obtain their perfect superimposition. We test our procedure in several experimental case considering holograms recorded in both microscope configuration and lensless configuration. Finally we give also a procedure, based on the National Television Systems Committee (NTSC) coefficients, to synthesize a single hologram that contains the information associated to the three colored numerical reconstructions. Numerical analysis and display tests are used to evaluate the effectiveness of the proposed method.

8430-05, Session 1

Computer-generated hologram tailored for dielectrophoretic PDMS patterning

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Dielectrophoretic clustering is obtained both for liquid and solid matter thanks to light shaping performed by phase only Spatial Light Modulator (SLM). We present a procedure able to perform two functions: design polymeric stable structures usable as microfluidic channels and trapping micro objects. These two tasks are combined to realize a single device.

The liquid matter is Polydimethylsiloxane (PDMS) and its patterning in microstructures is developed by means of photorefractive effect in a functionalized substrate. X-cut Iron-doped Lithium Niobate (LN) crystal is used as substrate while a thin film of PDMS is spin on it. When LN, covered by PDMS, is exposed to structured laser light, a space charge field arise that is able to induce self-patterning of the PDMS liquid film. The rearrangement of PDMS is due to the dielectrophoretic effect.

Light structuring is achieved by a SLM positioned in the conjugated plane of the LN crystals. PDMS devices we realized are microfluidic channels. The first step of our procedure is the computing of a suitable Computer Generated Hologram (CGH) to be displayed by the SLM. An ideal target is designed and given as input to an Iterative Fourier Transform Algorithm (IFTA) to calculate the CGH. The IFTA used has been implemented for this particular application and it's tailored to generate a continuous light intensity profile in the LN plane.

Then PDMS microstructures are cured to induce solidification. Such PDMS channels are then used to trap particles floating inside. Trapping is realized exploiting again dielectrophoresis induced by photorefractive effect. LN with PDMS channel is exposed to laser light which present, now, a periodic two-dimensional intensity profile. The charge distribution due to this second exposure is able to trap particle in the previously built channels.

We realize a device with high degree of flexibility avoiding the need of moulds fabrication.

8430-06, Session 2

Optical measurement of the layer thickness of transparent materials

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Surface metrology plays an important role in the field of product development and quality assurance, not only in micro systems technology. Here, nowadays increasingly materials are used that lead to systematic deviations if measured by conventional dimensional measuring techniques. One example are polymers like SU-8 that are used on the one hand as a photoresist for structuring of micro systems, on the other hand also as the material for forming micro structures themselves.

The accurate measurement of the structural dimensions like e.g. the thickness of films made from transparent materials is a challenging task for conventional optical instruments. It has to be taken into account that usually instead of the geometric thickness d the optical thickness nd (n: refractive index) is measured. In addition to that, measurement of these structures becomes even more difficult, if they consist of several materials with different behaviour regarding the applied measuring technique. In this case, also the different material parameters like absorption, dispersion, etc. have to be considered.

Within a project funded by the German Federal Ministry of Economics and Technology specifications for measuring the layer thickness for various combinations of transparent films and substrates are developed. Simultaneously, references and correction procedures are defined that allow a reliable determination of geometrical dimension with conventional optical measuring instruments.

Within the scope of this contribution, a white light interferometer and a confocal sensor is used to investigate the systematic deviation while optically measuring the thickness transparent layers. First results shw systematic deviations up to 100% compared to tactile investigaeations of the same samples. Taking into account the material parameters like refractive index etc. the results can be improved significantly. In addition to that the modelling of the interaction of the sample with the light used in this investigation provides some helpful information to further improve the accuracy of the optical measurement of transparent samples.

8430-07, Session 2

Full wafer metrology for chemically graded films

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Combinatorial CVD (chemical vapor deposition) is a thin film technology which has the ability to produce oxide thin films on large wafers with a chemical gradient in one direction and a thickness gradient in the perpendicular direction. Important technological application includes doped ZnO for low k materials, TiO2-x suboxides and doped LiNbO3 for optical waveguides. Full wafer metrology on such samples then allows for the detection of combined chemical composition and thickness with unique properties.

We have made a full wafer metrology instrument which maps the optical thickness and the sheet resistance with a typical lateral resolution below 400um. We discuss the performance of various algorithms to extract the optical thickness from the white light reflectance measurement in the case of very small thickness. The sheet resistance is measured with an array of four AFM-like conductive cantilevers, allowing accurate R measurement where the standard tungsten four probes destroys porous thin oxide films. As an illustrative example, we have measured the optical thickness and R on a 6" wafer of Nb doped TiO2 , both on silicon wafer and sapphire as a substrate.

8430-08, Session 2

Investigation of defects in nanocrystalline tin dioxide films

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Semiconductor gas sensing materials based on tin dioxide (SnO2) have been attracting a great interest due to their high sensitivity to harmful gases at ppm concentration level and the compactness of sensing devices. Nanocrystalline tin dioxide has improved sensor properties due to larger specific surface area available for chemisorption and surface reaction processes. CO and NH3 gas detection is an important task of personal safety, especially in the regions of motor transport congestion. Nanocrystalline gas sensitive materials based on SnO2 modified by

Pd or Ru were synthesized via a sol-gel route and their interaction with CO and ammonia studied by means of electron spin resonance (ESR) spectroscopy. Modification by Pd yields the material highly sensitive to CO in room temperature region, while Ru-modified SnO_2 is outstandingly sensitive to NH_3 at raised temperature. The materials have well detectable sensitivity to these gases on the concentration level of ambient air standards. We have detected that O_2- and OH radicals are the main type of defects in unmodified nanocrystalline tin dioxide. The modifying of tin dioxide by Pd and Ru is accompanied by formation of new defects in the samples: Pd+3 and Ru+3. The concentration of these paramagnetic species on the materials interacting with CO and ammonia gases decreased because of their transition to the diamagnetic state Pd+2, Pd0 and Ru+4, respectively. Pd3+ in SnO_2/Pd being rather passive in reaction with CO was attributed to Pd3+ stabilization by SnO_2 support. The unchanged OH radicals concentration on interacting with CO was explained by their recovery during the oxidation of CO. A large decrease of Ru3+ fraction in SnO_2/Ru on interacting with NH_3 is assumed to be due to oxidation by NO_2 evolved from ammonia conversion on the surface of the material. Hydroxyls released from the NH_3 oxidation gave rise to OH concentration increase in SnO_2/Ru detected by EPR technique.

8430-09, Session 2

Failure of thin organic films by a combination of shearography and electrochemical impedance spectroscopy: the new concept of resistivity

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A critical (steady state) value of the resistivity of different coatings was determined by a combination of optical shearography and electrochemical impedance spectroscopy (EIS). The behavior of organic coatings, i.e., ACE Premium-grey Enamel, white Enamel, beige Enamel (spray coatings), a yellow Acrylic Lacquer, and a gold Nail Polish, on a metallic alloy, i.e., a carbon steel, was investigated over a temperature range of 20-60 0C. The value of the resistivity of coatings was obtained by correlating the in plane displacement of the coatings, from optical shearography, and by the alternating current (AC) impedance (resistance) of the coatings, from the EIS. The integrity of the coatings with respect to time was assessed by comparison the measured resistivity to the critical (steady state) or asymptotic value of resistivity. By shearography, measurement of coating properties could be performed independent of parameters such as UV exposure, humidity, presence of chemical species, and other parameters which may normally interfere with conventional methods of the assessing of the integrity of coatings. Therefore, one may measure the critical (steady state) value of the resistivity of coatings, regardless of the history of the coating, in order to assess the integrity of coatings. In this investigation, the obtained data of shearography were correlated with the data of electrochemical impedance spectroscopy (EIS) in 3%NaCl solution in order to obtain the critical (steady state) value of the resistivity of coatings.

8430-58, Session 2

Effect of thin films on dynamic performance of resonating MEMS

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Continued advances in microelectromechanical systems (MEMS) technology have led to development of a multitude of new sensors and their corresponding advanced applications. Great many of these sensors (e.g., microgyroscopes, accelerometers, biological, chemical, security, medical, etc.) rely on either sensing elements or elastic suspensions that resonate. Developments of such sensors are being made possible because of creative designs and novel packaging based on use of some of the most sophisticated analytical, computational, and experimental solution (ACES) tools available today, also known as direct and indirect solution strategies. These strategies are also employed to overcome limitations due to inherent behavior of materials fabricated into miniature shapes subjected to extremely harsh operating conditions while satisfying very challenging specifications/requirements of their applications. Regardless of their applications, sensors are always designed to provide the most exact responses to the signals they are developed to detect and/or monitor. One way to quantify this exactness is to use the Quality factor (Q-factor). Most recent experimental evidence indicates that as the physical sizes of sensors decrease (especially because of advances in fabrication by sacrificial surface micromachining) the corresponding Q-factors become more and more dependent on thermoelastic damping (TED); thermoelastic internal friction is present in all structural materials. This form of damping depends on material properties such as coefficient of thermal expansion, thermal conductivity, specific heat, density, and modulus of elasticity. TED is also related to such design/operating parameters as resonator dimensions and temperature. MEMS sensors are typically fabricated out of materials that are mechanically sound at the microscale, but can be relatively poor electrical conductors. For this reason, areas of MEMS are coated with various thin metal films to provide electrical pathways. These films, however, adversely alter resonant properties of a device. To facilitate our study, microcantilever configurations were selected to test influence that thin metal films have on resonators. This paper reviews a theoretical analysis of the effects that thermoelastic internal friction has on the Q-factor of microscale resonators and shows that the internal friction relating to TED is a fundamental damping mechanism in determination of quality of high-Q resonators over a range of operating conditions. Furthermore, the analysis also shows that the Q of resonators can be critical to the development of modern sensors. Also, using silicon microcantilevers coated with aluminum films from 5 nm to 30 nm thick, on one as well as both sides, Q-factors are experimentally determined using the ring-down method. The ring-down method entails mechanically exciting the microcantilevers at their fundamental resonance frequency, abruptly stopping the excitation, and then measuring the decay of oscillation amplitude as a function of time. From this ring-down curve, the Q-factor of each microcantilever was determined. Experimental results show that as thickness of the aluminum film increases, Q-factor of the device decreases. Comparison of ACES results indicates good correlation, well within the limits based on uncertainty analysis. In addition, preliminary results also show a significant temperature dependence of the Q-factor of aluminum coated microcantilevers.

8430-40, Poster Session

Dynamic birefringence mapping

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Abstract. Recent years, there are many requirements for inspection techniques of an internal structure in functional polymer materials, stress mapping. Many kinds of measurement methods have been proposed, but no reports have described instruments satisfying for both dynamic and two-dimensional measurement. A high-speed area sensor with polarizes, which are set four different axis direction of each pixel to 0, 45, 90, 135°, is used for dynamic birefringence mapping. An algorithm for a Stokes polarimeter is proposed. By using this method, a time resolution is archived in 1 micro-second.

8430-41, Poster Session

Tomographic analysis of medium thickness transparent layers using white light scanning interferometry and XZ fringe image processing

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Medium thickness transparent layers are becoming increasingly important in various fields of materials science such as in micro-

electronics, nanotechnologies, polymer science, biomaterials and chemistry. Such layers are often complex, consisting of medium thickness (1 µm to 20 µm), multi-layer, heterogeneous and sometimes very rough surfaces. New techniques are required to characterise their structural, physical and optical properties at a local level. Optical Coherence Tomography (OCT), initially developed for medical applications, has recently been applied to materials analysis, but is more adapted to the characterization of very thick samples of up to several hundreds of µm. The axial resolution of OCT is limited to a few µm due to the use of near IR wavelengths and extended coherence length illumination sources. OCT in its present form is therefore not well adapted to characterising medium thickness transparent layers in which axial details of less than 1 µm need to be imaged.

White light scanning interferometry (WLSI) on the other hand, can be used for performing structural tomography of medium thickness transparent layers. In this case, though, the classical 1D signal processing techniques along Z typically used for surface measurement are insufficient in the tomographic mode, due to the reduced signal to noise ratio of signals from buried structures. We have developed a tomographic technique using WLSI in the visible part of the light spectrum using 2D image processing of the fringes in the XZ plane and a subsequent reduction in noise. The new technique is suitable for characterising medium thickness transparent layers in the thickness region of 1 µm to 20 µm with submicron axial resolution. Applications of the technique are illustrated by the characterisation of passivation layers on CMOS chips, Mylar films (3 µm), layers of hydroxyapatite (a biomaterial) and colloidal layers (10 µm).

8430-42, Poster Session

Scatter method for measuring roughness of very smooth surfaces: an analysis and preliminary results

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A novel method for measuring roughness and reflectance of very smooth surfaces is presented in the paper. It is based on the measurement of Total Integrated Scatter (TIS) parameter using a flat photodiode integrator rather than a conventional optical sphere or hemisphere. Thanks to that there is a possibility to get much less expensive and smaller instruments than traditional ones that could find its application for surface control purposes in a production area of wider range of companies. Unfortunately, decrease of the integrator dimensions could restrict its spatial frequency bandwidth causing measurement errors. Additional errors can occur because of the integrator flatness. Therefore, an analysis of the influence of those factors has been performed. Using results of the Rayleigh-Rice vector perturbation theory, relations showing influence of the range-of-acceptance angle on the measured TIS value have been shown. For the case when very smooth surfaces (e.g., silicon wafers, optical mirrors, precision metal elements) are investigated, the low border of the angle range is very critical and should be carefully selected. On the other hand, the upper limit can be even less than 20-30o what makes possible to find a compromise while designing the measuring unit. At such limit the influence of the integrator flatness is proved to be non substantial. In the paper we present some material surface parameters valuable for the performed analysis as well as preliminary results of sample measurements in a tentative unit. Obtained results confirm validity of further investigations in this research direction. A precise unit for investigating functional properties of the method is under development as well as it is planned to make comparison of the measurement results derived from this unit, Ulbricht sphere instruments and other methods.

8430-43, Poster Session

Precision topography of MOEMS by Moiré interferometry

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Moiré topography is full-field optical technique in which the shape of object surfaces is measured by means of geometric interference between two identical line gratings. The technique has found various applications in diverse fields, from biomedical to industrial and scientific applications. In many industrial metrology applications, contact less and non-destructive shape measurement is a desirable tool for, quality control and contour mapping. This method of optical scanning presented in this paper is used for precision measurement deformation or absolute forms in comparison with a reference (optical), optical component, micro mirrors, micro-lenses, on surfaces that are of the order of mm ^{2} and more, where new concepts of scientific instruments that could not conceive before the existence of MOEMS have appeared.The principle of the method is to project the image of the source grating on the surface to be inspected, after reflection, the image source grating prints to the topography of the object and is superimposed on the reference grating. The optical setup used allows the magnification dimensional surface up to 1000 times the surface inspected, which allows easy processing and reaches an exceptional sub-nanometric imprecision of measurements 0,3.10-9 m. According to the measurement principle, the sensitivity for displacement measurement using moiré technique depends on the frequency grating, thus a great effort has been made to get gratings with higher density. Currently, and according to the literature, we can produce grating with density of several thousand lines per millimeter, which can increase the detection resolution. This measurement technique can be used advantageously to measure the deformations generated by constraints on functional parts and the influence of these variations on the function. It can also be used for dimensional control when, for example, to quantify the error as to whether a piece is good or rubbish. It then suffices to compare a figure of moiré fringes with another previously recorded from a piece considered standard, which saves time, money and accuracy. This method of control and measurement allows real time control; speed control and the detection resolution may vary depending on the importance of defects to be measured.

8430-44, Poster Session

Optical characterization of a glass fibre with the use of low-coherent light (LED)

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In numerous cases there is a need to understand the nature of single particles. An empirical investigation intended to acquire in situ information in real-time may be realized by means of light scattering. Such an investigation is causal, i.e. quantitative properties of the particle under examination are deduced on the basis of some features of the registered and processed scattered radiation.

Causal inference on the basis of light scattered by a single, weakly absorbing, e.g. glass particle is not a trivial task and encounters numerous limitations. Light scattered by such a particle is a complex combination of diffraction, reflection, refraction, and absorption. Their mutual interaction give rise to various non-linear phenomena including resonance scattering. An overall description of the scattering problem requires solving Maxwell equations within, e.g. Lorenz-Mie theory framework. This approach, however, is complicated analytically, in particular when inversion of measurement data is considered. In short, the scattered field is non-linearly dependent on the particle properties. Besides, mathematical models of light scattering are usually ill-conditioned even if identifiable in theory.

The idea covered in this paper is to influence some spectral properties of the radiation incident on a transparent particle in order to dampen the effect of nonlinearities (ripples, resonance microforms) on the primary rainbow pattern, so that simple physical and mathematical interpretation in terms of the Airy theory of rainbow become applicable. This idea is intended to be a basis for a method for non-invasive characterization of a glass fibre of 125 µm nominal diameter. Key theoretical studies and numerical results include: discussion on low-coherent radiation scattering in the vicinity of the primary rainbow employing Lorenz-Mie theory, interpretation of macroscopic effects of scattering in terms of Debye series, and approximation of measurement data with the Airy model of rainbow. An empirical research is aimed to present some achievements in the formation and processing of the Airy rainbow with the use of high-

power light emitting diode (LED) as a source of low temporal coherence radiation.

8430-45, Poster Session

IR-SWLI for subsurface imaging of large MEMS structures

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Scanning White Light Interferometry (SWLI) permits imaging of MEMS devices for quality control purposes. Unfortunately non-destructive imaging of MEMS structures embedded in silicon is not currently available. For such MEMS devices IR-SWLI offers non-destructive quality control.

We developed such an instrument for non-destructive imaging of embedded MEMS structures. It comprises an IR-camera (XenIC, 0.9-1.7 µm), a Mirau-type interferometer objective (Nikon), a piezo scanner (PI) and a custom made IR-range LED-based light source. The light source combines multiple separately controllable LEDs with different wavelengths into a collimated homogenous beam offering an adjustable spectrum. We incorporated software based image stitching to allow large areas to be characterized.

We show large area 3D images detailing the three layers of MEMS cavities covered by silicon. The results are compared to ones acquired using destructive imaging by scanning electron microscopy and a SWLI setup equipped with a halogen lamp.

8430-46, Poster Session

Broadband phosphor conversion LED source for stroboscopic white light interferometry

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Stroboscopic broadband interferometry permits accurate characterization of rapidly moving small structures. Halogen lamps provide intense broadband output (high depth penetration/resolution) but cannot be switched rapidly (to capture high frequency oscillation). White LEDs can be switched rapidly but their discontinuous spectrum is narrow compared to halogen lamps. Multi-LED sources provide intense broadband light but footprint, thermal stability, and optics are issues. We show that phosphor LEDs can serve as semi-intense very broadband light sources featuring smooth spectra and high switching rates.

The need for reduced environmental impact has increased use of solid state light sources in e.g. instrumentation. LED based light sources feature high spectral stability, small thermal and physical footprint, short switching times, long operational lifetime, and little IR (thermal) emission. Unfortunately e.g. MEMS quality control using SWLI (scanning white light interferometry) requires continuous broadband emission, not available from current commercial LEDs. We address this issue by designing and building a phosphor-based LED source with a continuous broad spectrum.

We chose phosphor types, mass ratios, and encapsulant, to tailor a wide continuous emission spectrum. Based on known emission spectra, we mixed combinations of blue, cyan, yellow, and red down-conversion phosphors. The phosphor composite was excited with a modified UV LED (365 nm). UV provides primary excitation of blue phosphors (SCA ($Sr_{10}(PO_4)_6Cl_2:Eu$) and BAM ($BaMgAl_{10}O_{17}:Eu$)). The emission (≈450 nm) of the blue phosphor provides secondary excitation of longer wavelength phosphors: (YAG (yttrium aluminum garnite), strontium-barium silicate, and sulfoselenide).

We characterized our source with a HR2000+ - OO type spectrometer. The spectrum's FWHM was 241±1.5 nm; spectral drop was 30%. Pulse width was 45±5 ns when the LED was driven with 4 A at 20 V. We used the source for static MEMS measurements in a SWLI system. Obtained interferograms had FWHM of 740 nm with low side lobes (>15%).

8430-47, Poster Session

LED driver for stroboscopic interferometry

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Three different types of white diodes (wLEDs) and three types of single color LEDs were tested as light sources for stroboscopic scanning white light interferometry (SSWLI) for dynamic MEMS characterization. Short, intense, light pulses and low duty cycle (< 10%) are required to freeze the motion of an oscillating sample. Peak wavelength(s) were measured as duty cycle was increased from 1-10% at 100 kHz.

A custom designed LED driver was built utilizing a Metal-Core Printed Circuit Board (MCPCB). At the core of the circuit is a CMOS high speed high current gate driver (IXDD415SI). The LED driver is compact (50x110 mm), has good thermal resistivity (0.45 °C/W), wide bandwidth (~DC-10 MHz), and can drive single LEDs at 5A peak current (0.7% duty cycle at 1 MHz). The shortest measured electrical pulses were 6.21 ± 0.03 ns FDHM.

Minimum measured optical pulse FDHM (Full Duration Half Maximum) was 8.42 ± 0.03 ns using non-phosphor white LED (0.7 % duty cycle at 1 MHz) and 32.08 ± 0.03 ns using white phosphor-converted LED (0.7 % duty cycle at 1 MHz). Minimum optical pulse FDHM for single color blue/green (cyan) LED was measured to be 6.36 ± 0.03 ns. The maximum intensity of these pulses was 625.56 ± 36.48 µW and 543.48 ± 31.69 µW, respectively.

All types of white LEDs could be used for stroboscopic SWLI measurements at frequencies up to 2 MHz. For higher frequencies, non-phosphor white LEDs must be used in combination with cyan LED to avoid interferogram ringing.

8430-48, Poster Session

Theoretical model of volumetric objects imaging in a microscope

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Optical microscope is a well known instrument with many applications in biomedical imaging, precise measurements etc. Since its invention, a lot of imaging theories were proposed, describing the ways of lens parameters optimization for correction of aberrations and enhancement of image quality. Nowadays a lot of modalities arose, which utilize combination of a microscope arrangement with other optical techniques, such as holography or low-coherence interferometry. The most important features of these modalities are related to the diffraction or coherence effects due to such combination, rather than to exact ways of lens aberrations correction. Thereby for analysis and understanding of these effects we need a theoretical model, which would be rigorous enough to take into account the diffraction and coherence effects and in the same time simple enough to allow clear physical interpretation of the observed effects.

In this paper we propose such a model of volumetric object imaging in a microscope, which utilizes the theory of two-dimensional image formation and description of the influence of the observed object through its effective field. The applicability of the proposed model is shown by the examples of conventional full-field microscopy and digital holographic microscopy. The obtained results can be used for analysis of a wide range of modalities, including holographic microscopes, low-coherence microscopes etc.

8430-49, Poster Session

Simple method for measuring bilayer system optical parameters

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Thin layers as optical components are applied more and more frequently in novel optoelectronic devices. For development of such devices it is important to know the linear optical parameters and thicknesses of the layers. These parameters can be determined by analyzing light interference patterns in the transmittance or reflectance spectra. In this case one must seek an approximation of semi periodical function which can be quite complex. However, the main difficulty of this task is to generate initial guess of layer thickness and refractive index. This is due to the fact that wavelength difference of extreme points in the analyzed spectrum is defined by the product of both the layer thickness and refractive index.

Here a simple method for measuring bilayer system optical parameters in the low absorbance part of the sample transmittance and reflectance spectrum is proposed. In this method the layer thicknesses must be comparable to light wavelength to have more than one interference fringe in the spectrum. This is a mandatory requirement for the layer thicknesses in order to have at least one exact solution of problem. In such case the thicknesses and refractive indexes are determined by separating the interference fringes for each layer. This can be done by applying Savitzky - Golay smoothing filters with two different orders of polynomial fits and window lengths. During the approximation procedure it is assumed that the thickness obtained from permutations of all extreme points in the spectrum is constant. Thus the optimal penalty parameter for finding the solution is the standard deviation of thicknesses. In order to demonstrate the effectiveness of this method, results of thin organic film thicknesses and refractive indexes will be presented.

8430-50, Poster Session

Uncertainties of displacement measurement of nanometrology coordinate measurement machines caused by laser source fluctuations

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One of considerable sources of displacement measurement uncertainty in nanometrology systems such as multidimensional interferometric positioning for local probe microscopy is the influence of amplitude and especially frequency noise of a laser source which powers the interferometers. We investigated the noise properties of several laser sources suitable for interferometry for micro- and nano-CMMs (coordinate measurement machines) and compared the results with the aim to find the best option. The influences of amplitude and frequency fluctuations were compared together with the noise and uncertainty contributions of the other components of the whole measuring system. Frequency noise of investigated laser sources was measured by two approaches - at first with the help of frequency discriminator (Fabry-Perot resonator) converting the frequency (phase) noise into amplitude one and then directly through the measurement of displacement noise at the output of the interferometer fringe detection and position evaluation. Both frequency noise measurements and amplitude noise measurements were done simultaneously through fast and high dynamic range synchronous sampling to have the possibility to separate the frequency noise and to compare the recorded results.

8430-51, Poster Session

A micro-SPM head array with exchangeable cantilevers

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Due to its high spatial resolution, scanning probe microscope (SPM) has become an indispensable tool in various scientific disciplines and industrial fields, particularly for nanotechnology. However, traditional SPMs, using a single cantilever for topography imaging, embody such disadvantages like relatively low imaging speed. And the low scanning speed becomes in particular unacceptable for those nano-measuring machines, whose scanning table has a displacement range up to several tens of millimeters with nanometric resolution.

To enhance the performance of the currently available nano-measuring machines and effectively reduce the measurement time for large specimen, in this paper a micro-SPM head array is proposed, which consists of 1 × N (N = 7 in our case) micro-SPM heads, realized in one chip by MEMS technology.

The main part of the micro-SPM head is the MEMS-positioning stage, which is realized on the basis of an electrostatic lateral comb-drive actuator. In order to take the advantage of the high lateral resolution of conventional cantilevers, a flexible cantilever gripper was designed to be integrated into the MEMS-positioning stage within the SPM head. Now conventional cantilevers can be mechanically mounted onto the MEMS-positioning stage or dismantled from the MEMS-positioning stage after the tip is worn out. In this way, the well-designed and calibrated MEMS-positioning stage can be repeatedly and efficiently utilized.

Design, simulation and fabrication of the SPM-head will be detailed in this paper. Mechanical performance such as stiffness and eigenfrequencies of the micro-SPM heads were investigated. The in-plane displacement was calibrated with a laser interferometer and the result shows a quite good linearity. Preliminary experimental results proved the feasibility of the cantilever gripper design.

8430-52, Poster Session

High-speed phenomena visualization using digital holographic microscopy

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Capillarity phenomena in microchannels are important in many fields, mainly in biology and medicine, where water and blood circulation is vital. Lithography processes at nanoscale, for example microstructure fabrication in the surfaces of elastomers such as PDMS, are also influenced by capillary flows. In order to study this phenomenon in laboratory conditions, using a transparent narrow cuvette or microchannels, a high speed camera is necessary. Digital holographic microscopy is a suitable technique to study such as this, of fast phenomena in real time, because it allows full field recording in one single hologram of details from different depths of the investigated object without any mechanical scanning in the experimental setup. Furthermore, it enables transparent object visualization and analysis, without any contrast agent.

We used commercial microchannels or we built a cuvette using a glass slide and a coverslip, glued together with a double face scotch tape. In our experimental setup, based on the Mach-Zehnder interferometer with two additional identical microscope objectives in both arms, we recorded holograms of the free liquid surface rising. The recording medium is a video camera sensor (Photron SA1) which allows 512x512 pixels resolution at 10,000fps and 4s acquisition time. The reconstruction step is performed digitally using an algorithm based on the diffraction theory in Fresnel approximation and the 3D images of the dynamically moving surface are obtained from the phase shift introduced by the sample in the optical path.

We process the reconstructed object images to monitor liquid-air interface shape, velocity and contact angle as a function of the vertical ascending time. These are important elements which bring new information in the study of liquid viscosity, flows in microchannels or in natural capillary tubes. Experimental data from digital holographic microscopy is presented and also simulations for fluid flow using commercial software. For calibration we use some standard liquids. Samples with different concentrations of pollutants important in soil degradation is analyzed. This research is financed by the contract POSDRU/89/1.5/S/63700 and equipments by 4/CP/I/2007-2009 Capacities.

8430-53, Poster Session

Speckle reduction by simultaneous multiple radiations on the object in digital holography

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One of the most common problems in classical and digital holography is presence of speckle in reconstruction process. Speckle effect occurs when coherent light is dispersed by an optical rough surface. Due to using of coherent light in holography, speckle generation is inevitable. Speckles have a statistical distribution in size and intensity. Thus, complete elimination of them is impossible. But, one can use this statistical characters for reduction its effects.

Microscopic irregularity of an optical rough surface has a random distribution in depth. Then, in digital holography, by changing the object wave the resulted speckles will be changed.

In this work a method is presented for reducing the speckle effect. In this method a coherent beam is divided to two beams. One is used as reference beam. The other one after passing through a beam splitter splits to two parts. One part is guided to the object and after dispersing at the surface of the object arrives at the recording plane (CCD). The other part reaches to another beam splitter and splits to two beams. One of them is guided to the object and after dispersing at its surface arrives at the recording plane. The other part reaches to another beam splitter. The above process can be repeated for multi times. Transmission coefficient of the beam splitters is so chosen to produce object waves with nearly similar intensities.

In this way a hologram is produced. Reconstruction of this hologram generates an image that is a superimposition of some similar images but with different speckle patterns. Since the reconstructed real or virtual images are observed in the direction of reference beam, different wave objects lead to the images in the same location. Consequently, the resulted image has a smaller amount of speckle relative to an image generated with an object wave. Experimental results verify the above technique.

8430-54, Poster Session

Zero-order elimination in off-axis digital holography by digital processing

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In digital holography DC component is a tedious one and lowers quality of the reconstructed image.

Two simple methods are presented to suppress the DC term in off-axis digital holography. Zero-order intensity of a reconstructed hologram is uniform and great compared to twin images. By noting these characteristics one can derive and subtract the zero-order pattern from the original reconstructed image. To do this, two methods are proposed, one based on uniformity, and the other based on strength of the zero-order intensity.

1-Using Uniformity of Zero-order Intensity

Original image is reconstructed using the hologram. Another image is generated by shifting every column pixels of the original image to the next column, and shifting the last column pixels to the first column. This operation can be executed very easy by software like MATLAB. The two images are different except in the area occupied by the zero-order, though they are visually similar and not to be distinguishable. By comparing the two images, a third image is achieved that its pixels have zero value except the ones that are corresponding to the area occupied by zero-order component. This image actually is the zero-order component. Subtraction this image from the original one leads to an image with no zero-order.

2-Using Strength of Zero-order Intensity

First by comparing the values of the image pixels the maximum intensity value over the entire image is determined. In the second step an image is generated whose pixels have zero value except those pixels whose values are equal to the value of the most intense pixel. This image is too zero-order component. The image without DC component is achieved by the last procedure in the previous method.

Experiments show that processing by this method also leads to the results that are equivalent to the results obtained by the previous method.

8430-55, Poster Session

Low-cost pulsed solid state illumination for microPIV measurements

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Particle Image Velocimetry (PIV) is a non-invasive, full-field optical measuring technique, which has become a dominant tool for velocity measurements of fluids and gases in both macro (traditional PIV) and micro scales (microPIV). In PIV experiments, the fluid under investigation is seeded with tracer particles, which are shining under an excitation by a properly tuned light source. The idea behind the method is to precisely register the position of corresponding particles in two different instances of time and then from these records ascertain particle displacements, i.e. flow velocity. Pioneering PIV systems were designed in a laboratory environment by researchers to understand flow physics. In most PIV experimental setups, illumination is performed using dual cavity pulse lasers, whose outputs reach several hundreds mJ at pulse lengths in the range of tens of nano-seconds. These laser systems are very expensive and bulky. Today, overall cost of a moderate performance PIV system is above one hundred thousand Euros. In addition, the efficiency of these types of arrangements in microPIV experiments is very low, since a few tens of microJ is sufficient for the illumination of a microscope field-of-view inside a microchannel. In recent years, there has been an increasing trend in designing cost-effective and portable high accuracy PIV systems. In this work, we investigate a possibility to decrease the cost of microPIV systems by using a high power LED as an illumination source. For this purpose we developed an electronic circuit, which drives LEDs with a high current over a short duration. The driver circuit is triggered with the used CCD camera, and is able to produce single or double current pulses per camera trigger. Beside these, the drive circuit allows flexible adjustment of the pulse duration (from 1 μs up to tens of msec), the time delay between pulses (in double-frame mode), and time delay between trigger signal and current pulse. In this work, we present experimental results of flow velocity measurements with microPIV of water seeded with the 1-μm-diameter spherical-polystyrene-fluorescent particles in 30x300μm2 and 200x200 μm2 microchannel, where a LED (LumiLED, peak wavelength at 450 nm) is used at double-illumination mode with current pulses of up to 10 A with a duration of 5 μs. Beside this the behavior of various parameters of LEDs at high current pulse regime will be communicated.

8430-56, Poster Session

Interferometric-displacement readout of cantilever sensors

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Micro cantilevers are used as sensors for sensing various physical parameters such as temperature, acceleration or biological analysis and sensing. However, one of the major difficulties in using the cantilever sensors is the measurement of cantilever displacement. Many methods are devised for this goal; nevertheless, most of these methods are very elaborate and intricate. One of the common methods for measuring the cantilever displacement is by focusing a laser beam to the cantilever tip and detecting the reflected beam using a PSD (Position Sensitive Detector). However, this method is very sensitive to the alignment of the test setup. Another example takes advantage of the interference patterns on the cantilever due to the illumination of a laser beam. Nevertheless, in this method, the cantilevers should be transparent and therefore, this method could not be applied for conductive cantilevers. This paper explains a new method for measuring the cantilever displacement using both reflective and interferometric properties of the cantilever.

In our method, a Laser light is shone on the cantilever, and the reflected pattern is monitored by a commercially available CCD. Due to the micrometer dimensions of the cantilever which was smaller than the spot size of the laser, the laser beam would reflect from both substrate and the cantilever, and it will make an interference pattern on the screen. In this configuration, a displacement in the cantilever will reflect the light in a different angle and also changes the optical path difference between the reflected light from the cantilever and substrate. The overall result of these two effects would results in a displacement of the interference pattern, which could be simply measured using a CCD and by taking into account both effects, the cantilever displacement could be measured. For testing this technique different cantilevers were fabricated and were electrostatically actuated. By this method, displacements as small as 10nm were possible to measure.

8430-57, Poster Session

Improving the display quality of full color holographic projection system

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Hologram, as a type of diffractive optical element, is sensitive to wavelength in the processing of optoelectronic reconstruction. It introduces transverse and longitudinal chromatisms, which make the colorful imago fuzzy. In optoelectronic redisplay, the quality is also affected by the characteristic of the spatial light modulator used, for example, the ratio of active area and dead area (fill rate).It brings multi-order diffraction images, which spoils badly the useful reconstruction image. In the colorful holographic projection system, for it applies three color lasers as the light sources, usually there is color-break due to the switching of the different lasers, which also decrease the image quality. In order to improve the image quality of full color holographic projection system, in right of the effecting factors above, the paper analyzes how they affect the reconstruction image firstly. For a computer hologram, transverse chromatism and longitudinal chromatism are removed by resampling the object information and loading a specially designed virtual phase distribution in the computer hologram respectively. For decreasing the effect of multi-order diffraction images, it superimposes digital blazed grating to the phase hologram. For the problem of color-break, it proposed to update time sequence chart of laser. The paper also provides some experimental results to verify the measures above.

8430-10, Session 3

Real-time 3D vibration measurements in microstructures

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Measuring vibrations in MEMS with laser-Doppler vibrometry has become a standard analysis option in research and in production quality control of MEMS and other microstructures like read/write heads in hard disks. However, a typical vibrometer beam measures only displacements in direction of the impinging laser beam and, therefore, detects typically the motion perpendicular to the surface under test (out-of-plane motion). On the other hand, the measurement of in-plane vibrations is still a problematic task. Usually stroboscopic videomicroscopy is employed. But environmental noise is critical for stroboscopy and the typical achieved noise levels are between a few 1 nm (with averaging) and a few 100 nm. Therefore, vibrometry would also be the preferred technique for in-plane vibrations. It is possible for rough surfaces to collect scattered light if the measurement laser beam impinges with a tilt in respect to the surface normal. Thus, 3D vibrations in optical rough macroscopic structures are measured with laser-Doppler vibrometry from three different directions. The resulting three velocity vectors are transformed into a Cartesian coordinate system. This technique does also work for microstructures but has some drawbacks: (1) The surface needs to scatter light, (2) the three laser beams can generate optical crosstalk if at least two laser frequencies match within the demodulation bandwidth, and (3) the laser beams have to be separated on the surface under test to prevent optical crosstalk. Drawback (3) results in a possible measurement spot diameter of above 30 µm and drawback (2), if crosstalk cannot be accepted, limits the possible bandwidth. In this paper we show the possibilities and limitations of the current technology. Measurements, obtained with this approach demonstrate that the technique is well-suited within its limits for many technical problems and can measure vibration amplitude accurately and lead to impressive 3D animations of operational deflection shapes. However, we will also present a novel optical approach, based on the direction-dependent Doppler effect, which overcomes all the drawbacks of the current technology. We have realized a demonstrator with a measurement spot of 3.5 µm diameter that does not suffer optical crosstalk because only one laser beam impinges the specimen surface while the light is collected from three different directions. The paper discusses design aspect to achieve optimal amplitude resolution and minimal measurement spot size together with maximal depth measurement range. We demonstrate that we can obtain real-time signals of 3D-vibrations with pm-amplitude resolutions and bandwidths in the range of several tens of MHz. Therefore, our new technique will enable a wide range of new measurement tasks in microstructures. For example, it is possible to measure on a corner or edge of a MEMS device and to detect in-plane, vibration-amplitude spectra with sub-nanometer resolution in real-time. Of course, it is also possible to obtain operational deflection shapes by scanning.

8430-11, Session 3

Interferometry of AlN-based microcantilevers to determine the material properties and failure mechanisms

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During the last decade, special attention has been drawn to develop relevant metrological techniques to measure the reliability of MEMS which are not well established yet. Here, we investigate environmental effects on properties of piezoelectric microcantilevers, where aluminum nitride (AlN) is used as actuation material. The individual structure consists of a thin film of AlN sandwiched between two metal electrodes and deposited on top of a Si cantilever. The sample contains an array of such free-standing cantilevers with constant width of 50 µm and length ranging from 200 to 1000 µm. The environmental effects to be considered include thermal and humid cycling, as well as harsh electrical loading. First, we perform a series of tests under normal conditions to evaluate the influence of temperature, humidity and resistance on the behavior of microcantilevers. Then, we accomplish the accelerated life tests under harsh conditions, including the aging stimulated by an electrical loading, high temperature and high humidity, as well as resonant fatigue generated by applying high voltage to the electrodes of the piezoelectric transducer. A Twyman-Green interferometer (TGI), operating in both stroboscopic and time-average interferometry regimes, is used as a metrology tool.

We started by the evaluation of the operational behavior of 800-µm long cantilevers, investigating the impact of temperature variations on their initial deflection. We investigated also the influence of electrical properties on the operation of AlN cantilevers by analyzing two wafers including samples with different thickness of AlN (1.4 and 1.0 µm). The

experimental results show an important parabolic bending, proportional to the square of the applied constant voltage VDC. Here, a damping of resonance amplitude is more than 5X lower than for the cantilevers with proper insulating properties and operating at the same voltage level. Finally, we noticed certain instability in resistance for some cantilevers, which affects their performances. During the measurement of the displacement vs. constant voltage the resistance was changing from infinity to the order of hundred of Ω (or inversely). The initial linear behavior became a parabolic one.

The accelerated aging tests under an electrical load allowed us to determine the range of supply voltage at which the AlN microcantilevers is operating without failure. We observed that the maximal value of sinusoidal ramp exciting the 800-µm cantilevers to the resonance vibration is around 2 Vpp and 40 Vpp for the samples with 1.4 µm and 1 µm of AlN, respectively. Higher voltage generates a significant level of electrical stress that causes operational instability, which can be observed as a slight variation in the vibration amplitude. This is produced by resistance variations and electrical breakdown between the electrodes. We observed in static operation that the constant voltages out of the range ±15 V are too large for some 800-µm cantilevers, leading to their failure. The application of too high DC voltage can produce severe damages on the top metal electrode as well as degradations in AlN film. These damages cause delaminations of the thin film stack.

8430-12, Session 3

Advanced optical characterization of micro solid immersion lens

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We report on the versatile optical characterizations of microfabricated solid immersion lenses (µ-SILs) with 2 µm diameter, at visible wavelength (λ = 642 nm). Since aberrations are not limiting the performance anymore, such small SILs are more robust to the fabrication and alignment errors due to the wavelength-scale size. The fundamental characteristic, i.e. the spot size reduction, has been investigated by applying a focused Gaussian beam of NA = 0.9. Specific illuminating beams have also been applied for the beam-shaping of the immersion spots. For example, the doughnut-shape hollow beam is interesting to consider to illuminate µ-SILs to form particular spots with a submicron extension. For the optical characterizations with abovementioned fundamental and specific illuminations, a high-resolution interference microscope (HRIM), which incorporates a 100X/NA1.4 oil immersion objective and a Mach-Zehnder interferometer, is employed to monitor illuminating beams and measure the output spots emerging from the SILs. The three-dimensional (3D) amplitude and phase distributions of the focal spots with and without the µ-SILs reveal the information of the full width at half maximum (FWHM) and the full spot (Airy disc) sizes. Analysis of the 3D intensity data provides not only the transverse spot size but also the longitudinal spot size, and moreover the peak intensity enhancement that is caused by a tighter focus. The Bessel-Gauss beams of the zeroth order and the first order yield the smaller spot sizes in immersion condition. Furthermore, a focused beam with an azimuthal polarization, which exhibits a doughnut-shape focus, and a two-spot focused beam, when is demcomposed from the doughnut beam by a polarizer, are applied to illuminate the SILs. The shape of the spot is maintained but the size is reduced due to the corresponding immersion effect. Such structured focal spots are of significant interest in optical trapping, lithography, and optical data storage system.

8430-13, Session 3

Wafer-scale nondestructive metrology on subwavelength diffraction gratings by means of Wood's anomaly

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The shape and position of absorption resonances (Wood's anomalies) which arises from the excitation of surface plasmon polaritons (SPP) in reflective sub-wavelength diffraction grating are strongly dependent on grating parameters such as the grating period, the grating height and to a lesser extent, the grating duty-cycle and the grating profile. These resonances can therefore be used as a non-destructive metrology tool to estimate the grating parameters by reflectivity measurements and provide in some cases a good alternative to destructive SEM techniques. In this paper we briefly describe the theoretical conditions for which SPP are excited. We investigate the sensitivity of the reflectivity for individual grating parameter variations for CO2 laser wavelengths. Here we present theoretical and experimental data which by data fitting permit to estimate the wafer-scale (4") grating parameter uniformity on GaAs/Au diffraction gratings. A numerical electromagnetic grating solver software package "Gsolver" was used for the theoretical modeling. We show that this fully automated non-destructive testing method allows us to measure grating parameter variations of the order of 0.5 %. The measurement time needed to scan a 4" wafer has been shown to be of the order of a few minutes. This is much faster as compared to traditional techniques as (deconstructive) SEM inspection or white light interferometry. Furthermore, the extension of this technique to larger wafers does not impose any difficulties.

8430-14, Session 3

On topography characterization of micro-optical elements with large numerical aperture using digital holographic microscopy

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The paper is devoted to characterization of topography of micro optical elements with very high numerical aperture using digital holographic microscope. For very high numerical aperture we mean the one larger than numerical aperture of optical system conjugating the object plane with the detector plane. Therefore the optical system is not capable of capturing any information about micro element areas with high numerical aperture (high shape gradients). In the paper we are presenting method of recovering high numerical aperture shape from few measurements with digital holographic microscope working in Mach-Zehnder configuration. We are focusing on metrology of microlenses of numerical aperture of order of 0.5 or more. Within the presented method two or more measurements are performed. One measurement is carried out for an object orientation tangential to the illumination wave, in the next measurements an element is tilted against the illumination wave. When the element is tilted then some of optical field is coming from "new high gradient element area", when the element is tangential the area of high gradient is producing field with numerical aperture larger that numerical aperture of the measurement optical system. In our paper we therefore use data captured by these two (or more) measurements in order to reconstruct micro element topography with very high numerical aperture. To achieve this goal we present algorithm for reconstruction of micro element topography of high numerical aperture with tilted illumination. The algorithm is based on the analysis of local ray transition through measured object. Using this algorithm we can reconstruct shapes obtained for different angular orientation of element. The reconstructed shapes for different tilts of element are then merged into final reconstructed element topography with very high gradients. Accuracy of the developed algorithm is proved by simulation and experiment.

8430-15, Session 4

Advances in calibration methods for micro- to nanoscale surface measurements

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No abstract available

8430-16, Session 4

Quality assessment of aerospace materials with optical coherence tomography

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The increasing demand of the aerospace industry for new functional materials requires appropriate methods for quality assessment. It is a challenge nowadays to characterize materials with structures in the size of a few microns quickly, accurately and non-destructively. Optical coherence tomography (OCT) is a relatively new contactless and non-invasive technology for obtaining the internal structure of turbid materials. It is highly developed for biomedical imaging of tissues while OCT-based methods for non-biomedical investigation tasks, e.g. within the field of non-destructive testing for material inspection are rarely reported. Therefore, here we demonstrate and evaluate the suitability of OCT for the measurement of aerospace materials, e.g. coatings, polymer and glass fiber composites. An in-house designed OCT system is constructed using an optical source operating at 1550 mm to give a better penetration depth. Considering the scattering nature of the materials, a 99/1 fiber-optic splitter is equipped to guarantee enough light back to the fiber coupler for interference fringe generation. Moreover,2D galvo scanners and an optical delay line is also coupled in the system to make fast 3D volume imaging available. Finally in combination with appropriate image processing, e.g. envelope extraction, and noise reduction, the thickness and refractive index of thin films can be determined. The micro structure of materials is also shown for further defects detection.

8430-17, Session 4

Extrinsic calibration of a fringe projection sensor based on a zoom stereo microscope in an automatic multiscale measurement system

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For a flexible inspection of objects with a highly complex surface profile (for example small gears), an automatic multi-scale measurement system is used. The coarse position and form of the item is firstly sampled by a sensor measuring with low resolution but an extended field of view. In subsequent steps, indicator functions are iteratively applied to determine subregions in the registered data set which are then measured with sensors in a higher scale, hence higher resolution, in order to finally accomplish the given inspection task. To enable the measurement of micro system in our setup, we use a zoom stereo microscope which has been adapted to a fringe projection sensor. By changing the zoom value, the measurement fields can quickly be changed from 4 cm^2 to less than 1 mm^2. As prerequisite for a successful multi-scale inspection, every sampled data set, acquired in different scales (zoom-values) and at varying positions, must be registered in one global data model. This is only possible if the extrinsic coordinate transform from the sensor's internal coordinate system to the common, global coordinate system of the inspected object and its uncertainties are known. In this paper, we present an extrinsic calibration of this fringe projection sensor with respect to the world coordinate system. Of course, this calibration has to be done individually for every used scale, hence zoom-value, but in the presented setup, synergetic effects allow to simplify the process, since parts of the necessary transformation matrices are similar for every used sensor. Finally we show a 3D-measurement result of a gear, where several sampled patches are stitched together to one point cloud with the aid of the presented calibration.

8430-18, Session 4

Submicron resolution high-speed spectral domain optical coherence tomography in quality inspection for printed electronics

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We present the use of sub-micron resolution optical coherence tomography (OCT) in quality inspection for printed electronics. As we demonstrated in our previous publications OCT can be successfully applied in characterization of printed products [1-3]. However, existing devices rendered its day to day use as troublesome and inconvenient. This was either due to measurement speed or limited axial resolution.

The key component of an ultra-high resolution OCT system is very broadband light source, typically supercontinuum. So far, sub-micron axial resolution OCT required time domain approach [4], where depth dependent profiles were acquired by translation of the reference arm of the interferometer. The drawback of the technique is the data acquisition time, limited by the speed of the reference arm scanner.

The speed-wise alternative has been the spectral domain OCT, where typical system uses a fixed reference arm and a spectrograph to obtain the axial profile. Therefore, much higher, video-rate data acquisition is possible. Although SD-OCT is the most widely used approach, its main limitation in industrial applications is limited axial resolution. State of the art SD-OCT systems based on femtosecond lasers or broad-lighters (i.e., multiplexed superluminescent diodes) offer the axial resolution of ~3 µm [5]. However, in printed electronics, we deal with very thin layers, often close to or below one micron in thickness.

The solution is a device combining assets of both techniques i.e., sub-micron resolution spectral domain OCT. Such device employs supercontinuum light source based femtosecond laser followed by photonic crystal fibre. The spectral region of 400-800 nm is used for the measurements. Due to broadband probing beam free-space Michelson interferometer is used. The interference spectrum is acquired and analysed by a spectrograph based on diffraction grating, photo objective and line-scan camera. Measured axial resolution of the device equals 0.98 µm.

References:

1.J. Czajkowski, T. Prykäri, E. Alarousu,J. Palosaari, and R. Myllylä: Opt. Rev. 17(3), (2010) 257-262.

2.T. Fabritius, R. Myllylä, S. Makita, and Y. Yasuno: Opt. Express 18(1), (2010) 22859-22866.

3.J. Czajkowski, T. Fabritius, J. Ulanski, T. Marszalek, M. Gazicki-Lipman, A. Nosal, R. Sliz, E. Alarousu, T. Prykäri, R. Myllylä, and G. Jabbour, App. Phys. B, (2010) doi:10.1007/s00340-011-4699-5.

4.B. Povazay, K. Bizheva, A. Unterhuber, B. Hermann,H. Sattmann, A. F. Fercher, W. Drexler, A. Apolonski, W. J. Wadsworth, J. C. Knight, P. St. J. Russell, M. Vetterlein, and E. Scherzer, Opt. Lett. 27(20), (2002) 1800-1802.

5.B. Cense, E. Koperda, J. M. Brown, O. P. Kocaoglu, W. Gao, R. S. Jonnal, and D. T. Miller, Opt. Express 17(5), (2009) 4095- 4111.

8430-19, Session 4

Spectroscopic identification of materials with calibrated full-field optical coherence tomography in the visible range

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Since twenty years Optical Coherence Tomography (OCT) has found strong interest for imaging in turbid media. Recently, conventional OCT has been extended to spectroscopic investigation (SOCT). In this work we show that the interference conditions are not equal in the whole field of view, leading to errors in spectroscopic analysis with a full-field OCT. We propose a general calibration method for SOCT measurements which has been tested within a protocol, to perform spatially-resolved spectroscopic identification of materials with OCT.

We use a white light Full-Field Time-domain OCT with a Mirau objective (NA=0.4) [1]. A Köhler illuminator provides a 180×250 µm observation field on the sample. The objective is scanned over a 30µm-depth by means of a piezo transducer.

The fringe spacing of the z-interference signal on a point (x,y) of the field depends on the numerical aperture of the microscope objective [2]. Because of some geometrical effects due to lighting conditions, we found that the effective cone aperture varies with (x,y). It results in a (x,y)-dependent fringe spacing and a spectral shift of the reconstructed spectra ($\Delta\lambda$=20nm at 100µm from the axis), following a homothetic factor β(x,y). The measure of β on a reference sample yields a correction function implemented to our spectral measurements in order to get relevant spectroscopic information over the total field. The method has been applied for reflectivity measurements of a plane gold sample, in very good agreement with the ones obtained with a spectrometer. It has been successfully applied for gold identification on a mixed sample (Silicon and Gold).

[1] Gael Latour et al., Optics Communications, vol. 283, pp. 4810--4815, 2010.

[2] Arnaud Dubois et al., Appl. Opt., vol. 39, pp. 2326--2331, 2000.

8430-20, Session 4

Evaluation of nano-level 3D shape extraction system using RGB color interference fringes

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Nano-level 3-D measurement is a key technology for the current and future generation of production systems for semi-conductors, LCDs and nano-devices. The requirements from these productions are 1) nano-level measurement accuracy, 2) 10 micro-meter level measurement range, and 3) high speed to be used in mass-production line. To meet with these requirements, wide range nano-level 3-D shape measurement method using combination of RGB lights has been developed. It measures the height of nano-objects from only one image of RGB lights interference color fringes.

To analyze the RGB color fringes, the adaptive phase analysis method of interference fringes has been developed and achieved its accuracy. The method is based on the phase-shift method. The combination of RGB lights phase-shifts is able to expand the measurement range more than one wavelength of light. But it cannot measure the shape of step edges. To meet with the difficulty, the color analysis method on xy color signal plane has been introduced. RGB lights generate rainbow color fringes on an object image. Its color reflects its height. So, from the phase-shift data, the color change according to the object height is simulated on the xy color signal plane. According to the simulated color change, the shape of the step edge can be detected. The combination of the phase measurement method and the color analysis method has measured the 4 micrometer columns precisely.

Introducing the combination method, the accuracy and measuring range are evaluated. The experiments show that the accuracy of the measurement is around 10 nm. The current measuring range is around 5 micro-meter. To define the best noise filter, several experiments have been introduced. 3x3 Gausian filter is best to have good accuracy with small noises.

As more practical application, the shape of AFM needle has been extracted, successfully.

8430-21, Session 4

The elimination of the errors in the calibration image of 3D measurement with structured light

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The accuracy of the calibration points' image coordinates which used for the calibration of 3D measurement with structured light directly influences the system's measurement accuracy. There are some kinds of error in calibration image, such as the non-uniform illumination of the circles on calibration board, the non-uniform illumination of the projected circles, non-unniform intensity in images caused by image's paraxial non-uniform intensity, the error aroused by camara's perspective modle, etc. These factors bring errors to the calibration points' extraction, and degenerate the final results. Aiming at getting high-precision and steadily image coordinates of calibration points, the calibration points on the calibration board and for projection are designed to be circle, and a novel real-time algorithm is presented, which is able to eliminate perspective bias, amends camera's image's paraxial non-uniform intensity error and non-uniform illumination error.

To start with, mathematical models are founded which respectively describe perspective error and camera image's paraxial non-uniform intensity error. Secondly, the model of light intensity reflected from calibration board which illuminated by a projector is built. Then, based on mathematical analysis and the consistant of the system(a DMD projector, a CCD, a black calibration board which is Lambertian reflector with white circles, a high-precision screw rail platform.) a solution for eliminating errors in CCD calibration images is proposed: 1) Using a projector as light source, a series image of calibration board moved with high-precision screw rail platform is acquired by a CCD. And the high-frequency noise is suppressed by median filter. 2) According to image's paraxial non-uniform intensity model and light intensity model, non-uniform illumination is eliminated. Step1: Get the preliminary image coordinates of ellipses' (circle on object plane turns into ellipse in image when the two planes are not parallel) center and the intensity of ellipses in one image. Step2: Using the centers' coordinates and average intensity of each ellipse as constraints, an interpolation result approximated to the real light intensity is gained. Then the non-uniform illumination is eliminated according to the interpolation result. Step3: Calculate preliminary calibration result after all images eliminated by repeating step1 and step2. 3) The perspective error of points' coordinates is corrected by preliminary calibration result and the mathematical model. Final CCD calibration result is calculated using corrected coordinates again. The calibration process of projector is similar to CCD.Finally experiment results indicate that the calibration error is reduced by 10% under the non-uniform illumination

8430-22, Session 5

Carrier and aberrations removal in interferometric fringe projection profilometry

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A profilometer, which takes advantage of polarization states splitting technique and monochromatic light projection method as a way to overcome ambient lighting for in-situ measurement, is under development [1]. Because of the Savart plate which refracts two off-axis beams, the device suffers from aberrations (mostly coma and astigmatism). These aberrations affect the quality of the sinusoidal fringe pattern.

In fringe projection profilometry, the unwrapped phase distribution map contains the sum of the object's shape-related phase and carrier-fringe-related phase. In order to retrieve the 3D shape of the object, the carrier phase has to be removed [2, 3].

An easy way to remove both the fringe carrier and the aberrations of the optical system is to measure the phase of the test object, measure the phase of a reference plane with the same set up and subtract both phase maps. This time consuming technique is suitable for laboratory but not for industry.

We propose a method to numerically remove both the fringe carrier and the aberrations. A first reference phase of a calibration plane is evaluated knowing the position of the different elements in the set up and the orientation of the fringes. Then a fitting of the phase map by Zernike polynomials is computed [4]. As the triangulation parameters are known during the calibration, the computation of Zernike coefficients has only to be made once. The wavefront error can be adjusted by a scale factor which depends on the position of the test object.

References

1. P. Blain, F.Michel, Y. Renotte, S. Habraken, Using a Savart plate in optical metrology, Proc. SPIE 7791, 779107 (2010).

2. H. Guo, M. Chen, P. Zheng, Least-squares fitting of carrier phase distribution by using a rational function in profilometry fringe projection, Opt. Lett. 31 (24) (2006) 3588-3590.

3. C. Quan, C. J. Tay, L. J. Chen, A study on carrier-removal techniques in fringe projection profilometry, Opt. Laser Techn. 39 (6) (2007) 1155-1161.

4. Daniel MALACARA, Optical shop testing ((John Wiley & Sons, England,2007)

8430-23, Session 5

Optical analysis of orange peel on metallic surfaces

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In this contribution, the orange peel on highly polished metallic surfaces was analysed by means of a 3D interferometric microscope [1] and also using spectroscopic ellipsometry [2]. Firstly, the surface topography of polished metallic samples, in particular the shape of the orange peel, was determined using a phase-shifting interferometer. This metrological 3D analysis showed that the orange peel can be seen as a periodic waviness of the surface. Then the optical properties of the investigated samples were studied via spectroscopic ellipsometry at various incident angles. These ellipsometric measurements proved that the samples have isotropic optical properties. In addition, it was found that the resulting pseudo-dielectric function in the entire range from 1.5 eV to 2.5 eV - as obtained based on the measured ellipsometric parameters [3]- does depend on the surface topography of the samples. By this experimental finding it is then immediately shown that spectroscopic ellipsometry can be applied to qualitatively describe the orange peel on highly polished metallic surfaces.

[1] ISO/DIS 25178-603:2009, Geometrical product specification (GPS) - Surface texture: Areal - Part 603: Nominal characteristics of non-contact (phase shifting interferometric microscopy) instruments.

[2] Hiroyuki Fujiwara, Spectroscopic Ellipsometry Principles and Applications, Wiley, 2007.

[3] D.E. Aspens, A.A Studna, Dielectric functions and optical parameters of Si, Ge, GaP, GaAs, GaSb, InP, InAs, and InSb from 1.5 to 6 eV., Physical Review B, 27:985-1009, 1985.

8430-24, Session 5

Optical characterisation of highly polished surfaces

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The fineness of the surface structure on highly polished metallic sheets is a major criterion for their quality and hence their industrial performance. Therefore a suitable quality control, e.g., of the visual appearance of these surfaces, can lead to remarkable cost reduction in industrial finishing processes. During these processes, polished metal sheets are in many cases affected by characteristic surface defects, like the orange peel, for example. This is a characteristic surface feature which is manifesting in a more or less ordered structure of fine peaks and valleys. In this work, the orange peel is optically investigated on 18 highly polished metallic samples. In this manner, it is shown that carefully selected surface height and functional volume parameters as determined by means of confocal microscopy and phase shifting interferometry (PSI) [1] are in good agreement with the visual appearance of the orange peel on the polished samples. Consequently, confocal systems and especially phase shifting interferometry (PSI) can be applied to quantitatively control highly polished metallic surfaces.

[1] ISO/DIS 25178-603:2009, Geometrical product specification (GPS) - Surface texture: Areal - Part 603: Nominal characteristics of non-contact (phase shifting interferometric microscopy) instruments

8430-25, Session 5

Determination of the metrological characteristics of optical surface topography measuring instruments

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The use of optical areal surface topography measuring instruments has increased significantly over the past ten years as industry starts to embrace the use of surface structuring to affect the function of a component. This has led to a range of optical areal surface topography measuring instruments being developed and becoming available commercially. For such instruments to be used as part of quality control during production, it is essential for them to be calibrated according to international standards. The ISO 25178 suite of specification standards on areal surface texture measurement presents a series of tests that can be used to calibrate the metrological characteristics of an areal surface topography measuring instrument (both contact and optical). Calibration artefacts and test procedures have been developed that are compliant with ISO 25178. The artefacts include crossed gratings, resolution artefacts and pseudo-random surfaces. Traceability is achieved through the NPL Areal Instrument - a primary stylus-based instrument that uses laser interferometers to measure the deflection of the stylus tip. Good practice guides on areal calibration have also been drafted for stylus instruments, coherence scanning interferometers, scanning confocal microscopes and focus variation instruments.

8430-27, Session 6

Iterative least squares integration method for shape reconstruction from gradient

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This work keens on improving the least squares integration method with iterative compensation to solve the issue that the imperfection of biquadratic shape assumption. Simulations are carried out to investigate the feasibility and superiority of the proposed method. Significant improvement in accuracy is verified by comparing with the traditional least squares integration method. Moreover, a comparison with the RBFs based integration method is carried out, and the results show the accuracy of both methods are comparable. The merits of the proposed method are accurate, fast, and able to handle large datasets. In summary, this least squares integration with iterative compensation method is an effective and accurate 2D integration tool to handle shape from slope problems in some gradient measuring based optical inspection applications.

8430-28, Session 6

Application of linear systems theory to characterize coherence scanning interferometry

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Coherence scanning interferometry is a versatile three-dimensional imaging technique that is widely used for the measurement of surface topography and is an increasingly popular alternative to traditional contact stylus profilers. It is a non-contacting optical method that combines the lateral resolution of a high power optical microscope with the axial resolution of an interferometer. For the case of weakly scattering three-dimensional objects, linear systems theory can be used to characterize coherence scanning interferometry by means of the point spread function in the space domain, or equivalently the transfer function in the frequency domain. In this paper, linear systems theory is extended to include strong scattering from the interface between two homogenous media of arbitrary refractive index.

Measurement of the point spread function gives the response of the system to a point object, but this direct approach is difficult to achieve in practice and multiple scattering effects from a point object would violate the validity of the linear theory. A more practical approach is to deduce the point spread function from the system response to a known surface. In this paper the point spread function of a coherence scanning interferometer is measured using data obtained from a mercury sphere. The measurement is compared with an ideal system.

8430-29, Session 6

Measurement of rectangular edge and grating structures using extended low-coherence interferometry

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Rectangular step-like and grating-like structures in combination with specular surfaces play an important role in micro-technology, e. g. MEMS and MOEMS fabrication. In addition, rectangular grating structures are often used to calibrate optical profilers and to determine the so-called cut-off wavelength of an instrument in order to characterize its lateral resolution.

Due to its outstanding depth resolution capabilities low-coherence or white-light interferometry (WLI) is one of the most used optical techniques in this field. Unfortunately, step height structures often lead to disturbing effects known as batwings in WLI measurement. On a measured profile these effects overlay the real profile heights of a rectangular grating. As a consequence, the lateral resolution capabilities and the transfer characteristics of white-light interference microscopes are difficult to characterize. In general, the lateral resolution of such instruments is assumed to agree with the lateral resolution of a conventional light microscope for 2D imaging and the measurement process of an optical profiler is assumed to be linear similar to a microscopic imaging process.

Our results show that there are significant differences between the instrument transfer function of a white-light interferometer and the optical transfer function of a conventional microscope. In this context we analyze the transfer characteristics of current white-light interferometers based on theoretical considerations, simulation studies, and experimental investigations. It turns out that under certain conditions a correct measurement of a rectangular profile is possible even if only the first order diffraction component is captured by an objective lens with a given numerical aperture.

In this contribution the limitations of current instruments are discussed and new approaches to overcome existing limits will be introduced:

In order to reduce the batwing effect we combine a Mirau white-light interferometer with a confocal illumination system. Since the confocal scanning process is much faster than the integration time of the used CCD camera there is no further restriction of this approach with respect to the measuring speed of a conventional white-light interferometer. Furthermore, it is shown that an adaption of the central wavelength of the low-coherent light can improve the measurement accuracy significantly if rectangular profiles are obtained from the phase information inherent in WLI signals.

8430-30, Session 7

SLM-based microscopy

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In microscopy it is customary to use a wide variety of imaging methods. Unfortunately, for most of these it is necessary to physically alter the setup (filters, special objectives, etc.). We present a programmable microscope in which an integrated spatial light modulator(SLM) is incorporated in order to realize a number of otherwise physically intricate modifications. We employ a HDTV LCOS SLM (Holoeye Pluto, 1920x1080 pixel, 8 µm pixel pitch), two different LED illuminations in reflection and transmission, an Olympus UmPlanFl 50x with a NA of 0.8 and a CCD camera(SVS-Vistek eco204 1/3”) with 1024x768 resolution. By the use of computer generated holograms(CGHs) we were able to recreate a number of classical phase contrast imaging techniques such as Zernike phase contrast or DIC. For this we used locally differing phase gratings on the SLM, resulting in light destributions that correspond to the concerning methods. This also simplifies the modification and combination of such approaches. We were successful in creating mixed phase contrast methods such as DIC-Darkfield and Zernike-DIC enhancing the properties of the imaging process. Additionally, the SLM empowers us to compensate for the normal kinds of aberrations such as coma, astigmatism and spherical as is shown on a small scale grid. Another method consists of halfing the exit pupil and steering the light propagating over each half onto different regions on the CCD. The resulting two images with halfed NA can be considered as images from differing perspectives depending on pupil size and NA. By combination we can, through the tools of stereomicroscopy, reach a pseudo threedimensional object representation. Other imaging methods like structured illumination or confocal microscopy are also possible if the setup is extended to a state in which not only the imaging light but also the illumination light is propagated over an SLM with a CGH.

8430-31, Session 7

Combining digital holographic microscopy and optical tweezers: a new route in microfluidic

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An optical configuration is realized to obtain quantitative phase-contrast maps able to characterize particles floating in a microfluidic chamber by interference microscopy. The novelty is the possibility to drive the sample and measure it thorough the same light path. That is realized by an optical setup made of two light beams coming from the same laser source. One beam provides the optical forces for driving the particle along the desired path and, at same time, it works as object beam in the digital holographic microscope (DHM). The second one acts as reference beam, allowing recording of an interference fringe pattern (i.e., the digital hologram) in an out-of-focus image plane. This work finds application in the field of micromanipulation as, the devise developed allows to operate in microfluidic chambers driving samples flowing in very small volumes. Recently, the field of optical particle micro-manipulation has had rapid growth, due to Optical Tweezers development. A particle is trapped or moved along certain trajectories according to the intensity and phase distribution of the laser beam used.

Here, particles freely floating are driven by optical forces along

preferential directions and then analyzed by a DHM to numerically calculate their phase-contrast signature. The improvement is that one laser source is employed for making two jobs: driving and analyze the sample. We use two slightly off-axis laser beams coming from a single laser source. The interference between them gives the possibility to record in real-time a sequence of digital holograms, while one of the beam creates the driving force. By this method, a great amount of particles can be analyzed by a real-time recording of DH movies. This allows one to examine each particle at time and characterize it. The optical configuration and the working method are illustrated. Experimental results are shown for polymeric particles and in-vitro.

8430-32, Session 7

Quantitative differential interference contrast (DIC) microscope with fast modulation of bias and shear direction

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Differential interference contrast (DIC) light microscopy is widely used ways to revealing detailed structures and motion in unstained living cells and observing small steps on the surfaces of semiconductor wafers. DIC microscopy is a beam-shearing interference system in which the reference beam is sheared by a small amount, generally by somewhat less than the diameter of an Airy disk. The technique produces a monochromatic shadow-cast image that displays the gradient of optical paths. Those regions of the specimen where the optical paths increase along a reference direction appear brighter (or darker), while regions where the path differences decrease appear in reverse contrast. As the gradient of optical path grows steeper, image contrast is significantly increased. Another important feature of the DIC technique is that it produces effective optical sectioning. This is particularly obvious when high numerical aperture (NA) objectives are used together with high NA condenser illumination.

A conventional DIC microscope shows the two-dimensional distribution of optical path length gradient encountered along the shear direction. Thus contrast of DIC images varies proportionally with the cosine of the angle made by the azimuth of the optical path length gradient and the direction of wavefront shear. It is therefore necessary to examine unknown objects at several azimuth orientations.

To overcome the limitations of available systems, we have built an assembly, which allows the bias and shear directions to be switched rapidly without mechanically rotating the specimen or the prisms. The assembly consists of two standard Nomarski prisms with liquid crystal polarization rotator in between. When the polarization rotator is in OFF state, the total shear direction of the assembly is at +45-deg to the shear direction of the first prism. If the polarization rotator is in ON state, the total shear direction is at -45-deg to the shear direction of the first prism. Thus, when one would switch the polarization, the shear direction would be rotated by 90-deg.

We added one assembly to the illumination path and another one to the imaging path of the standard Olympus BX-61 microscope. Also one variable liquid crystal retarder was installed into the microscope in order to change a bias. Four raw DIC images at two orthogonal shear directions and two inverse biases are captured and processed within a second. Then the quantitative image of refractive index distribution within a thin optical section is displayed on a computer screen. The obtained data can also be used to compute the quantitative distribution of refractive index gradient or height. It is also possible to generate enhanced, regular DIC images with any desired shear direction. New DIC microscope can be combined with other techniques, such as fluorescence and polarization microscopy.

8430-34, Session 7

Wide-field scanning microscopy with optical super-resolution

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The Microsphere-based Misoscopic-lens Microscopy (MMM) is a newly developed optical super-resolution method which works under wide-field white light illumination. Although it possesses multiple advantages, the viewing field of 3M system is fundamentally confined by the size of the microsphere, and thus its performance in practical utilizations is distinctly limited. We proposed a new strategy to permanently overcome this barrier. By sticking a microsphere on a glass probe, the microsphere hence can move followed with it. The probe was then fastened to a piezo scanner so that the microsphere can be artificially controlled to scan on the surface of the sample. By using the digital image processing algorithms, the ultimate image can be stitched to a larger scale. This method can not only expand the effective viewing field, but also make the sample free from the pollution caused by the deposited microspheres. We authenticated the feasibility of our visualization by using a piece of Blu-ray Disk as the sample and a microsphere with a diameter of 4.38μm. To avoid the possible fluctuation of the microsphere due to the roughness of the sample during the scanning process, the microsphere was semi-immersed in the liquid droplet. Besides the more stable movement, liquid immersion also brings additional advantages, including the strengthened contrast and faster capture speed of the final image.

8430-35, Session 8

Ellipsometric detection of optical trapped nanoparticles by periodic localized light

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The purpose of this study is development of a system for trapping nano particles by periodic localized light and confirming trapped nano particles by measurements with an ellipsometoric method. In recent years, production of nano particles is performed actively. Nano particles are of interest for some different attractive properties with a bulk body in terms of increasing of reactivity. Those attractive properties are applicable to production of an optical element and a device. In production of nano particles, it is necessary to actuate nano particles and to measure trapped particles without contact in micro region. In this study, trapping nano particles can be achieved by periodic localized light. For producing a localized light, we have used diffraction by using the periodic nano structure. When a periodic width of periodic nano structure is shorter than a wavelength of trapping light, periodic localized light is generated by the diffraction on the structure. Evaluation of trapping can be achieved by comparing ellipsometrical parameter with rotation analyzer type ellipsometric method. In confirmation of effectivity this system, this letter reports results of periodic width with periodic nano structure dependence of polarization properties of trapped nano particles and of trapping light intensity dependence of trapping volume of nano particles. From experimental results, nano particles were found to be trapped by periodic localized light. In addition, trapping volume was found to increase with increasing in trapping light intensity. Based on these results, this system achieved trapping and confirming nano particles.

8430-36, Session 8

Fiber-top and ferrule-top cantilevers for atomic force microscopy and scanning near field optical microscopy

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Fiber-top and ferrule-top cantilevers (FTC) are a new generation of all optical, monolithic, self-aligned microdevices. They are obtained by carving a cantilever on the cleaved end of an optical fiber (fiber-top) or on a ferrule terminated fiber (ferrule-top). FTCs rely on Fabry-Perot interferometry to measure the deflection of the cantilever with subnanometer deflection sensitivity. FTCs specially developed for scanning probe microscopy are equipped with a sharp tip that has the dual function of probing the topography and collecting/emitting light. We perform the scanning probe microscopy using these probes in air, liquid and at low temperature (12°K). The light emission/collection functionality of FTC probes also allows one to combine scanning near field optical microscopy (SNOM) and optical transmission microscopy with contact and non-contact mode atomic force microscopy (AFM). This makes FTCs ideal for AFM+SNOM on soft samples, polymers and biological specimen, where bent fiber probes and tuning fork based systems would not be recommended because of the high stiffness of those probes.
We demonstrate here the capability of fiber-top cantilevers to measure deflection and collect near field optical signal, and also the capability of ferrule-top cantilevers for simultaneous optical transmission microscopy and topography of SNOM gratings. Thanks to their unique features, FTCs also open up possibilities for UV nanolithography and on-demand optical excitation at nanoscale.

8430-37, Session 8

Real-time characterisation of non-metallic inclusions by optical scanning and milling of steel samples

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The cleanliness of steel is described by the amount, size, composition, morphology, and distribution of non-metallic inclusions (NMIs). These nonmetals are present because of natural physical-chemical effects, and because during continuous casting steel is accidentally contaminated with slag, refractories, and materials of casting moulds. NMIs influence the properties of steel. Therefore, a combined milling and image processing system is proposed that mills and scans slices of steel samples to retrieve volumetric information about NMIs. The system is capable of scanning steel samples of 300x100x90mm in size at spatial resolutions of either 3, 5, 10, or 20µm and a volumetric resolution of 10µm within a few hours. After each milling operation the steel surface is captured by a moving large-area CCD image sensor. The optical system further consists of a distortion-free macro lens and diffuse coaxial lighting for brightfield illumination. Additional results using dome lighting and bar lights for darkfield illumination are presented. The interaction of an NMI with the milling cutter results in non-homogeneous NMI reflectances which bear information about its mass density and chemical compound. Although the steel surface is highly reflective the milling cutter creates a periodic pattern of moldings which becomes accentuated by shadows of light. An adaptive wedge filter in the Fourier space dampens those artifacts. NMIs are binarized separately in every image by local thresholding. In order to reduce segmentation artifacts neighbouring slices of the volumetric stack of images are filtered using morphological operators. A statistical analysis of the segmentation results estimates the macro cleanliness. Furthermore an interactive 3d visualisation enables the exploration of NMIs and their distribution within the sample. Different viewing, filtering and sorting capabilities are implemented, like ordering NMIs w.r.t. their shape factor. It is expected that the study of these attributes leads to information about the composition and formation of NMIs.

8430-38, Session 8

Plasma surface figuring of large optical components

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Fast figuring of large optical components is well known as a highly challenging manufacturing issue. Different manufacturing technologies including: magnetorehological finishing, loose abrasive polishing, ion beam figuring are presently employed. Yet, these technologies are slow and lead to expensive optics. Variants of plasma based processes have been researched. Plasma processing is an attractive alternative solution for meter scale optical surfaces as it promises much shorter figuring times and much lower operational costs as it does not require a vacuum nor does it employs expensive consumables. In this paper, fast figure correction of large optical surfaces is reported using a Reactive Atom Plasma (RAP) process. We have previously reported that RAP processing of 150mm size optics to Lambda /40 (λ=632.8nm) can be achieved with a cycle time of 20 minutes. The work reported in this paper will show achievements in scaling-up the RAP figuring process to 400 mm size optical surfaces of 420mm square shape Corning ULE® substrates of 40mm thickness. Spherical surfaces of 3 metres radius of curvature with 2.5 micrometre P-V (500nm RMS) form accuracy and 2 nanometre roughness have been figure corrected using a 1.2 metre capacity using the HELIOS 1200 re-active atom plasma figuring system. The HELIOS machine is a unique 3 axis CNC controlled sub-aperture plasma processing system employing novel time-dwell and tool path control strategies. Form accuracy measurements before and after figure corrections were carried out using a vertically configured optical test tower employing a Zygo Dynafyz interferometer. Measurement repeatability of the optical test tower and substrate has been assessed at better than 20nm PV. Figuring results, together with the processing times, convergence levels and number of iterations, for 400mm size optical surfaces will be reported. The results illustrate the significant potential advantage of plasma processing for figuring correction of large silicon based materials. Results enable an accurate forecast of the reduced processing time and cost of the large optics needed for important future programmes such as high power laser systems, EUV systems, earth orbiters and astronomy projects.

8430-39, Session 8

Nanoscale patterns made by using a 13.5-nm Schwarzschild objective and a laser produced plasma source

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LiF is a radiation-sensitive alkali halide widely used in radiation dosimetry, optoelectronics and integrated optics. In the color centers, F2 and F3+ radiate visible light under optical excitation by 450nm pumping light. As a result, indirect detection of the EUV images in LiF can be obtained with submicron resolution by using a fluorescence microscope. The Schwarzschild objective consisting of two spherical multilayer mirrors are widely used in EUV imaging and nanolithography. For making nanoscale patterns, we set up a Schwarzschild objective with the demagnification of 0.1 and the numerical aperture of 0.01 in the object space, which leads to 0.4msr acceptance angle for the imaging system. The Mo/Si multilayers which have high reflectivity at 13.5nm were deposited using magnetron sputtering techniques. The measured reflectivity achieves 68.7%, which was measured in National Synchrotron Radiation Laboratory (NSRL). The roughness of substrates and accuracy of thin films deposition are the main reasons which decrease the reflectivity of Mo/Si multilayer optics. EUV radiation is produced by focusing the Nd: YAG laser onto a cylindrical Cu target which is located in chamber with vacuum degree of 10-2 Pa. The pulse duration of laser is 20 ns, the maximum energy is as high as 0.8 J, the focal spot diameter is 200 µm approximately. Diameter of the plasma is 300µm, which is measured by a pinhole camera. In this

presentation, using LiF crystal as EUV detector and a Schwarzschild objective working at 13.5nm as imaging system, mesh images with 4.2μm, 1.2μm and 800nm line width and pinhole patterns with 1.5μm diameter are acquired in projection imaging mode and direct writing mode, respectively. Fluorescence intensity profiles of images show that the resolution of mesh image is 900nm, and the one of pinhole image is 800nm. In the experiments, a spherical condense mirror based on normal incidence type is used to eliminate the damage and contamination on the masks (mesh and pinhole) caused by the laser plasma, and the energy density is not decreased compared with that the masks are close to the plasma. The development of the Schwarzschild objective, the alignment of the imaging system and the imaging experiments are also reported.

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8431-01, Session 1

Second and third order nonlinearities in silicon waveguides

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Nonlinear silicon photonics is a novel and very promising research field where a strong research effort has been spent in the last decade worldwide. The demonstration of optical devices like linear and nonlinear ultrafast electro-optical modulators, frequency converters, comb generators, etc, starts to appear in literature. Here we report on our recent study of the various nonlinearities that can be present in silicon waveguides and of their possible exploitation in optical, electro-optical and THz nonlinear devices. Additionally we will concentrate our attention on a possible way, we recently proposed and demonstrated, to extend the order of the optical nonlinearities available to the silicon material itself. Future possible all-silicon nonlinear optical devices operating in the NIR to FIR spectral range will be then reviewed.

8431-02, Session 1

High-gain nonlinear silicon photonics

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Nonlinear effects in Si photonic wires at telecommunications wavelengths bands have been shown to provide a fascinating and useful medium for nonlinear optical physics and applications in data communications. This paper will discuss recent nonlinear studies by our group at wavelengths > 2000nm. In particular, two-photon absorption (TPA) in Si vanishes at wavelengths approaching λ = 2200 nm, while its nonlinear Kerr coefficient n2 remains nearly that in the telecommunications bands. Hence, the nonlinear figure of merit (FOM) ($n2/\beta\lambda$) increases dramatically near silicon's above the two-photon absorption wavelength threshold. This large FOM produces an ideal platform for efficient, broadband, coherent nonlinear optical processes when incorporated into high-index-contrast dispersion-engineered photonic wires. This materials system can be used for chip-scale near-to-mid-IR applications including molecular spectroscopy, free-space communication, and environmental monitoring. In this talk, we will describe our work in a 4-mm-long Si wire near-to-mid-IR optical parametric amplifiers (OPA) with on-chip gain over a 220 nm bandwidth and discuss attainment of broadband mid-IR modulation instability (MI) gain with a bandwidth >580 nm centered at a ~ 2170 nm pump wavelength. This intense MI spectrum correlates with unprecedented values, i.e. >40dB, of on-chip parametric gain.

8431-03, Session 1

Silicon on sapphire and SOI photonic devices for mid-infrared and near-IR wavelengths

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Silicon on sapphire and SOI photonic devices for mid-infrared and near-IR wavelengths.

Conventional SOI waveguide technology, serving as the foundation of near-IR photonics, meets its limitation in mid-IR due to high loss associated with the buried oxide. Silicon-on-sapphire (SOS) waveguides are considered as a good mid-IR alternative, because sapphire has a transparency window up to 6µm and SOS waveguides are compatible with silicon on insulator (SOI) technology. In this paper we will present recent developments SOS and SOI based photonic devices. In particular we showed that properly-designed SOS waveguides can facilitate frequency band conversion between near-IR and mid-IR. Utilizing this, we propose an indirect mid-IR detection scheme, in which mid-IR signal is down-converted to telecommunication wavelength (1.55 µm) through SOS waveguides and indirectly detected by near-IR detectors. We analyze performance of this indirect mid-IR detection scheme. Particularly we model and compare the noise performance of this indirect detection with direct detection using state-of-the-art mid-IR detectors. We show that, in addition to advantages of room temperature and high speed operation, the proposed indirect detection can improve the electrical signal-to-noise ratio up to 50dB, 23dB and 4dB compared to direct detection by PbSe, HgCdTe and InSb detectors respectively. The improvement is even more pronounced in detection of weak MWIR signals. In order to further boost the performance, we also investigate mechanisms to increase the conversion efficiency in SOS waveguide wavelength converters. To this end, we show that efficiency can be enhanced by periodically cascading SOS waveguide sections with opposite dispersion characteristics to achieve quasi-phase-matching. This can provide >30dB conversion efficiency enhancement and increase the conversion bandwidth by 2 times. Such improvement may facilitate the fabrication of parametric oscillators that can improve the conversion efficiency by 50dB. Additional parametric devices and other nonlinear silicon devices compatible with near-IR and mid-IR wavelengths will be discussed in detailed.

8431-04, Session 1

Nonlinear silicon photonics

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Since the birth of nonlinear optics, researchers have continually focused on developing efficient, ultrafast nonlinear optical devices that require low optical powers. Silicon nanophotonics has emerged as a highly promising platform for such devices and for enabling massively parallel, integrated optical and electronic devices on a single chip. The basis for nonlinear photonics in Silicon is the strong light confinement that enables both a high effective nonlinearity and tuning of the waveguide dispersion, which is essential for phase matching of parametric nonlinear optical processes such as four-wave-mixing (FWM). We demonstrate a wide range of devices based on FWM in Si waveguides that offer the potential for ultrahigh bandwidth all-optical processing, CMOS-compatible multiple-wavelength sources, and all-optical switches.

8431-05, Session 1

Efficient four-wave-mixing-based wavelength conversion in silicon nanowire rings without dispersion engineering

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The recent progress in the fabrication of silicon nanowires has been very beneficial for, amongst others, four-wave-mixing (FWM)-based wavelength conversion applications. With careful optimization of the nanowire cross-sectional structure to appropriately tune the waveguide dispersion, one can establish phase-matched FWM with a high efficiency for pump-signal wavelength differences exceeding 400 nm in the near-infrared telecommunication domain, as demonstrated recently. Nevertheless, specific applications in domains such as spectroscopy, sensing, and biomedicine could benefit from wavelength conversion possibilities in both the near-infrared range and the mid-infrared region beyond 2 µm. It is extremely challenging, however, to engineer the dispersion of a silicon waveguide such that phase-matched FWM is obtained for large pump-signal wavelength differences both in the near- and mid-infrared spectral regions. As such, for these specific applications, the challenge is to enable efficient FWM for a large pump-signal wavelength difference in a spectral domain where the dispersion characteristics of the silicon nanowire are not optimally engineered for phase-matched FWM.

In this paper we propose an efficient FWM-based wavelength conversion scheme in a silicon nanowire ring whereby no dispersion engineering of the nanowire is required. Instead, we rely on the spatial variation of the Kerr susceptibility around the ring to quasi-phase-match the wavelength conversion process for TE polarized fields. Besides explaining the basic principle of this quasi-phase-matching scheme, we show through modeling that in the absence of dispersion engineering this quasi-phase-matched wavelength conversion approach can outperform 'conventional' wavelength conversion by as much as 10 dB. Taking also into account that the quasi-phase-matching scheme can be implemented for 'standard' waveguide geometries that adhere to the fabrication restrictions of mass-manufacturing foundries, this novel wavelength conversion approach is a promising method that can provide high efficiencies in circumstances that are less favorable for conventional conversion techniques.

8431-06, Session 2

Structural modification of second harmonic generation in silicon

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Photonics devices made of silicon are promising candidates for replacing certain micro-electronic components, where ultrafast processing is needed. Their main advantage is the fact, that both rely on the same material system and therefore share the same processing technology. However, most of this devices work only in the linear optical regime. This is due to the fact that for silicon the nonlinear optical effects, which are usually based on a second order nonlinear susceptibility, are hampered, because the generating tensor vanishes in the bulk due to its inversion symmetry.

To utilize the second order susceptibility, it is therefore necessary to develop concepts for modifying the second harmonic signal. One possibility is the application of inhomogeneous strain, which can break silicon's centrosymmetry close to the surface, thereby enhancing the second harmonic signal.

Here we investigate the second harmonic signal of structured and unstructured silicon, strained by a silicon oxide layer. The structured silicon consists of a periodic grating with rectangular teeth. The grating is created by means of laser interference lithography and a dry etching process.

The strain distribution inside the strained teeth is investigated theoretically by finite element simulations. High resolution x-ray diffraction (HRXRD) and TEM cross section electron diffraction are carried out to confirm the strain distribution, which is also compared to the strain in unstructured silicon samples. Furthermore the azimuthal distribution of the second harmonic signal, measured in a reflection geometry, of the unstructured sample and the grating is presented. It can be observed that the reduced rotational symmetry due to the nanostructuring has a profound effect on the second harmonic signal of the (111)-Si-surface leading to an increased directionality of the SHG-signal.

A first simple model, approximating this effect as a convolution of the SHG-signal of the original (111)-surface and the characteristic reflection properties of the silicon grating structure shows good agreement with the experimental data.

8431-07, Session 2

Energy efficient all-optical signal processing in SOI: nanowires or slow-light structures?

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In this paper we analyze and compare the energy performance of silicon-on-insulator (SOI) nanowires and slow-light photonic crystals in chip-scale nonlinear optical processes. The mature silicon platform presents a tremendous opportunity to develop hybrid electronic/optoelectronic circuits. These integrated devices offer the promise of unprecedented functionalities at ultralow energies in a cost-effective manner. To this end, wavelength scale waveguides known as 'nanowires' and slow-light photonic crystals are under intense investigation as key components in the silicon photonics paradigm. From device footprint, fabrication control, and energy consumption, the geometries of nanowires and photonic crystals present distinct advantages and challenges. Slow-light structures, with their enhanced light-matter interaction, are often heralded as a path towards sub-millimeter, energy efficient, silicon photonics. Light travelling at a reduced group velocity, typically greater than c/20 in photonic crystals, causes a buildup of localized light intensity much larger than traditional 'fast-light' waveguides, thus allowing nonlinear effects at reduced input energy. Nonlinear operations such as self-phase modulation, four-wave mixing, and all-optical switching in devices just hundreds of microns long have already been demonstrated employing slow-light. The instantaneous four-wave mixing (FWM) process is of particular interest due to its versatility in performing all-optical signal processing functions. In recent years FWM experiments in parametric wavelength conversion, switching, logic, parametric gain, time-lenses, all-optical demultiplexing, and phase-conjugation have been demonstrated in these two platforms. However, it is not obvious from current experimental progress which of these media offers a clear advantage. This is the first comprehensive quantitative energy analysis of nonlinear effects in these two common waveguide geometries. We incorporate real experimental conditions, including slow-light scaling of both nonlinear and linear optical processes, in addition to device bandwidth. Our results delineate regimes where nanowires and slow-light photonic crystals exhibit salient advantages and limitations. These results suggest a road map towards energy efficient silicon photonics.

8431-08, Session 2

Investigation of Si/chalcogenide hybrid slot waveguides

P. W. Nolte, C. Bohley, J. Schilling, Martin-Luther-Univ. Halle-Wittenberg (Germany)

In the last years great efforts lead to a strong miniaturization of optical components, as several devices were realized on the silicon-on-insulator (SOI) platform which is to CMOS technology. The very high refractive index contrast between the Si core (n=3.5) and the oxide cladding (n=1.45) and air (n=1), respectively, leads to a high confinement of light inside a waveguide. However, for many applications active devices exhibiting a nonlinear optical behavior are needed. One possible way to boost the nonlinear optical properties in integrated optics is the functionalization of SOI-structures with chalcogenide glasses creating a new type of hybrid devices. Chalcogenide glasses (e.g. As2S3) exhibit a nonlinear figure of merit of about Re $\chi(3)$/Im $\chi(3)$= 10 in the near infrared. This is more than an order of magnitude better than silicon itself. Using chalcogenide glasses for the nonlinear processes willtherefore minimize two photon absorption enabling efficient nonlinear optical devices for frequency conversion and optical switching which operate at high intensities.

Here we present slotted SOI-waveguides which have been clad and infiltrated by chalcogenide glasses to enhance their optical nonlinear properties. The slotted Si-waveguides have been fabricated using electron beam lithography and RIE-etching. They were subsequently coated with chalcogenide glasses (As2S3) using pulsed laser deposition.

The linear optical properties of the clad waveguides were investigated using a fiber coupled laser setup, which is tuned over a broad spectrum (1490 - 1640 nm) with 1 pm steps. Thus the mode index and propagation losses can be determined from a Fourier evaluation of the Fabry Perot oscillations of the transmission spectra.

The nonlinear properties have been studied by means of degenerate four wave mixing. Here, two laser beams with frequencies ω1 and ω2 interact with each other through the 3rd order nonlinear susceptibility of the waveguides. Thus two new beams with the frequencies ω3 = 2*ω1 – ω2 and ω4 = 2*ω2 – ω1 are formed. The ratios ω3/ω2 and ω3/ω2 determines the conversion efficiency which will be mapped depending on the spectral resolution ω2-ω1. From the conversion efficiency and its intensity dependence the averaged 3rd order nonlinear susceptibility $\chi(3)$ for the hybrid waveguide device is determined.

Thus we demonstrate how hybrid silicon/As2S3 waveguides can perform nonlinear frequency conversion via four wave mixing extending the functionality on the SOI integrated photonics platform.

8431-09, Session 3

40Gbit/s germanium waveguide photodetector on silicon

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Implementation of fast optical links in integrated circuits is picking speed up in order to keep pace with the datacom and telecom roadmaps. For this purpose, the development of photonic building blocks based on silicon is occurring, with technological and scientific breakthroughs in the fields of light sources, modulators and detectors. Near infrared Photo-Detectors (PDs) have been investigated quite in depth the last decade, with high responsivity and high bandwidth. We report a Ge photodetector which was selectively grown at the end of silicon waveguide. A very high optical bandwidth estimated at 120 GHz is shown, with a responsivity as high as 0.8A/W at a wavelength of 1550 nm. Open eye diagrams at 40Gb/s were obtained under zero-bias. These ultra-fast performances of Ge integrated photodetectors constitute a new milestone towards new generations of several Tbs/s chips merging electronic and photonic building blocks and devices.

8431-10, Session 3

Si:Ge nanowire photodetectors

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Photocarrier dynamics in semiconductor nanocrystals, such as quantum dots and nanowires, are often modified to produce substantially high responsivity with its spectral modulations due to their unique geometries at nanometer scale. For example, light absorption can be spectrally tuned by the enhanced optical field resonance in semiconductor nanowires, as well as the quantum confinements in semiconductor quantum dots, and also the photoconductive gain can be significantly amplified due to the temporal charge separation at highly populated surface and interface states. Thereby, bottom-up nanowires can serve as a model platform to investigate the integrated photonic and electronic processes in a strong light-matter coupling regime, since the low-dimensional potential variations can be easily built within individual NWs during syntheses. Here, we demonstrated an on-nanowire energy-band graded photodetection within an axially graded $Si_{1-x}Ge_x$ (0 1-xGe $_x$ nanowires serve as a test vehicle to investigate photocarrier dynamics along the engineered local potential at the nanometer scale in the extended wavelength range in a Si monolithically integrated circuitry. We systematically investigated how the energy density of these surface states evolve with respect to the continuous band modulation, pertinent to the relative Si:Ge composition, particularly for the photocarrier trapping and scattering. Specifically we find that the spectral on-set of interband photocarrier generation, and the amplitudes of photocurrent and photoconductive gain under the visible light are demultiflexed into the multiple output signals within individual Si:Ge nanowires over the continuously varying surface trap-state density in the range of 1.5×10^{11} cm^{-2} (Si) and 4.3×10^{12} cm^{-2} (Ge), as well as the dressed bulk energy band-gap modulation. Our study suggests general implication for the heteroepitaxial integration of broadband Si nanophotonic components.

8431-11, Session 3

Size-dependent photoconductive gain in Ge nanocrystal

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Photocarrier dynamics in semiconductors are the basis of the operation of photodetectors, photodiodes and solar cells, and they typically include photogeneration of electron-hole pairs, their efficient transport and collection as the output signal. When these photogenerated carriers are efficiently collected into photocurrent before their recombination, a photoconductive gain can be achieved, which usually serves as a measure of the photodetection efficiency. In semiconductor nanowires, this photocarrier dynamics is strongly affected by carrier trapping and scattering at the significant population of localized energy states at the surfaces over the bulk energy states, particularly due to their large surface-to-volume ratio. Earlier examples of the nanowire photodetectors imply that photoelectric processes in semiconductor nanowires can be strongly influenced by temporal and spatial charge separation and carrier multiplication within one-dimensional confinements. Thereby the photodetection characteristics must be size-dependent at the certain characteristic length scales, however, it has been scarcely reported in a quantitative way, and their unique nanosize-effects have yet to be fully exploited.

Here we report a strongly diameter-dependent photoconductive gain in intrinsic Ge nanowire ohmic photodetectors. Particularly we employed a spatially resolved photocurrent imaging technique with a 532 nm-laser beam along the individual Ge nanowoire channels, which enables to specify carrier transport as a function of photon flux and applied electrical field in quantitative manners. We first provide evidence that the photocarrier transport is governed by the hole drift along the NWs, giving rise to the higher internal gain up to ~10^3 from the thinner Ge nanowires. Second, we show that the magnitudes of both photoconductivity and gain are inversely proportional to the NW diameter (d) ranging from 50 to 300 nm, as photoconductivity and gain ~ $(1/d)^n$. We attribute these observations to the variation in the population of the surface-trapped electron upon varying diameters of Ge nanowire, and the concurrent variation in the effective hole density by an electrostatic interaction at the NW surfaces. A model calculation based on Poisson-Boltzmann equation of the diameter-modulated hole accumulation is consistent with the observed diameter-dependent photoconductivity variation. Our observations show inherent size-effects of internal gain in semiconductor nanowires, because the nanowire photoconductors are the ohmic-contacted, intrinsic Ge nanowires, i.e. the channel is free of extrinsic dopants under the uniform electrical field. Thereby our study provides a new insight into the photocarrier dynamics in nano optoelectronics.

8431-12, Session 4

Group IV photonic devices for the mid-infrared

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Group IV mid-infrared photonics is attracting more research interest lately. The main reason is a host of potential applications ranging from sensing, to medicine, to free space communications and infrared countermeasures. The field is, however, in its infancy and there are several serious challenges to be overcome before we see progress similar to that in the near-infrared silicon photonics. The first is to find suitable material platforms for the mid-infrared. In this paper we present experimental results for passive mid-infrared photonic devices realised in silicon-on-insulator, silicon-on-sapphire, and silicon on porous silicon. We also present relationships for the free-carrier induced electro-refraction and electro-absorption in silicon and germanium in the mid-infrared wavelength range. Electro-absorption modulation is calculated from impurity-doping spectra taken from the literature, and a Kramers-Kronig analysis of these spectra is used to predict electro-refraction modulation. We examine the wavelength dependence of electro-refraction and electro-absorption, finding that the predictions suggest longer-wave modulator designs will in many cases be different than those used in the telecom range.

8431-13, Session 4

Grating couplers in thick rib SOI waveguides for TE and TM polarizations

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Silicon-on-insulator (SOI) is an attractive photonic platform due to its integration potential and CMOS compatibility. However, when interfacing with external ports such as optical fibers, the large difference in refractive index and size of SOI waveguides and optical fibers results in a low coupling efficiency. Various fiber-chip couplers based on facet coupling have been demonstrated. Coupling through the chip surface using grating couplers is another promising approach as it allows wafer scale testing without the need for facet preparation.

Although the use of grating couplers on nanometric SOI waveguides has been extensively studied, the grating coupler in a micrometric rib SOI waveguide was demonstrated only recently. The implementation of grating couplers in thick SOI waveguides is complicated by the fact that, unlike in Si-wires waveguides wich suport only a fundamental Bloch mode, the grating region in thick SOI waveguides supports higher order Bloch modes. To overcome this problem, we proposed the use of an inverse taper, which efficiently suppresses the excitation of the higher order modes. This approach allows grating couplers to be fabricated using i-line stepper lithography with a single etch step, with a measured fiber-to-chip coupling efficiency of -2.2dB for transverse-electric (TE) polarization.

The avaliability of efficient grating couplers for transverse-magnetic (TM) polarization is important for a number of aplications, for example telecommunication transciever circuits based on polarization multiplexing or waveguide evenescent field biological or chemical sensors. It is known that sensors based on photonic integrated circuits benefit form strong and highly localized evanescent field of TM-like fundamental mode propagating in the waveguides to increase sensibility.

We demonstrate that the use of an inverse taper as access stage of grating couplers in thick SOI waveguides provides single mode excitation over a broad wavelength range. Using this approach, high-efficient grating couplers are demonstrated for both TE and TM polarizations.

8431-15, Session 4

Design, fabrication, and characterisation of fully etched TM grating coupler for photonic integrated system-in-package

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Grating couplers are the best solution for testing nanophotonic circuits. The main benefit is that they allow access via an optical fiber from the top and therefore there is no need to dice the chip and prepare the facets crucially. In the PLATON project grating couplers have to be designed to couple TM mode into and out of the SOI waveguides. The goal of the PLATON project is to combine the use of small-footprint, high-bandwidth plasmonic structures with silicon nanophotonics and electronics on a SOI motherboard to enable Terabit routing. The combination of both the SiP technology and the optical interconnects form the so called Photonics Interconnection Layer for Converged Microsystems using System-in-Package Technology (PICSiP).

Recent simulations came up with a grating coupler layout capable of theoretical coupling losses lower than 3dB for 1550 nm in TM configuration. The layout has been optimized for a simple integration scheme which is in the focus of PLATON since all components are finally integrated into one chip . Three different structures were considered in the first moment. A fully etched grating structure was chosen for fabrication simplicity and the optimal filling factor was found.

The structures were fabricated using proximity error correction (PEC) and show a uniform coupling efficiency for all couplers. Therefore they are well-suited for all applications which demand for stable fiber-to-chip coupling.

The spectral response of the structures was measured from 1500 to 1580nm with 2nm step and measuring the fiber-to-fiber losses of three straight waveguides equipped with three grating couplers with different periods. The optimal period grating exhibits adequate coupling losses slightly higher than 4 dB per coupler at 1550nm, being therefore the most promising design.

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8431-16, Session 4

WDM filter in Si photonic crystal technology with individual channel fine-tuning capability

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We demonstrate, for the first time compact and integratable solution for a multi-channel WDM filter with fine-tuning capability of individual channels. The filter is based on Si photonic crystal technology and can be integrated with CMOS processes.

Fabrication technologies of Si integrated WDM systems have significantly advanced over the last decade. However, up to date, the most difficult challenges are posed by wavelength accuracy control in WDM system manufacturing as well as wavelength drifts and variations during system operation. The proposed novel design of the multichannel integrated filter is based on the 1D silicon photonic crystal (PC) model. By infiltration of the certain grooves of 1D PC with matching filler, an efficient coupled Fabry-Pérot microresonator can be realized in which a wide stop band (SB) is used for frequency channel separation. By using nematic liquid crystal as filler, continuous tuning of the individual channels up to 30% of the channel-spacing can be achieved. The fabricated multichannel filters have the bandwidth of 0.1-0.9 nm with 20 dB extinction ratio.

8431-17, Session 4

Narrow band forward coupling using Bragg reflectors

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Add-drop multiplexers combining operation of a directional coupler with a Bragg reflector (BR) are known from years. Until recently, only contra-directional coupling schemes were considered for achieving the add-drop operation. In the present work, we address the problematic of forward directional coupling by revisiting the operation principles of the BR assisted couplers. We show namely that an efficient narrow band forward coupling operation can be achieved by an appropriate engineering of the BR waveguide dispersion properties.

Our theoretical analysis reveals the existence of a minimum Bragg grating coupling strength for co-directional phase matching. This threshold coupling condition is an essentially new aspect of Bragg grating asymmetric directional couplers (BGADC) as compared to conventional co-directional couplers and Bragg reflectors. The threshold condition is analytically determined, and a coupled mode theory (CMT) four-wave model is successfully applied to describe the behavior of the investigated device.

It is shown that the optimal BGADC operation is achieved with only one Bragg reflector distributed along one of the two waveguides. Furthermore, device behavior critically depends on whether the BR is located on the waveguide with lower or higher effective index. Operating the coupler with the BR on the low group index waveguide turns to be not suitable for most practical applications. Conversely, operating the coupler with the BR on the high group index waveguide leads to a significant improvement of the wavelength selectivity. This selectivity is a factor of 5.5 higher than that of conventional asymmetric directional couplers made of vertically coupled InGaAsP/InP waveguides with different alloy compositions.

Aside from the greatly improved selectivity, another important feature of this device is the very versatile operation that can be achieved by slightly changing its design. Single or dual band transmission operation, frustration of co-directional coupling are only a few examples of its functional possibilities.

A numerical validation of CMT results is performed for the case of slab waveguides with Bragg reflector assisted coupling. The proposed design is shown to be compatible with existing micro-nano-fabrication technology.

8431-61, Session 4

Reducing the temperature sensitivity of SOI waveguide-based biosensors

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Label-free photonic biosensors fabricated on silicon-on-insulator (SOI) wafers are interesting for their compact size, high evanescent field strength at the silicon waveguide surface, and volume fabrication potential. However, due to the large thermo-optic coefficient of water-based biosamples, the sensors are temperature sensitive. This drawback is shared by other biosensors based on refractive index measurement, such as the commercially successful surface plasmon resonance based sensors. Consequently, active temperature control is usually employed in such sensors, but for low cost, mobile, lab-on-chip applications, active temperature control is often not feasible, due to the additional size and cost it incurs.

Here, we make use of the opposite polarity of the thermo-optic coefficients of solid silicon and liquid water, and design, fabricate, and characterize a waveguide with a distribution of power between sample and silicon that significantly reduces the waveguide temperature sensitivity. The design is accomplished through the use photonic slot-waveguides, thus enabling improved control of the distribution of power between core and cladding.

Based on finite element simulations, we designed three waveguides close to the athermal point, and three asymmetric integrated Mach-Zehnder interferometers for characterization of the waveguides. We fabricated the devices by electron beam lithography and plasma etching on an SOI wafer with a 220 nm device layer and a 2 µm buried oxide. We used the negative electron beam resist hydrogen silsesquioxane (HSQ) and etched the device layer in a Cl2/HBr/O2/Ar plasma. We then studied the effective group index and temperature sensitivity of the devices operating with Cargile 50350 fused silica matching oil as top cladding, in the wavelength range from 1460-1580 nm. For the three different guides, the group index varies from 1.9 to 2.8 at 1530 nm, and the temperature sensitivity ranges between -70 and -160 pm/K.

8431-18, Session 5

Ring resonator silicon optical modulator based on interleaved pn junctions

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Silicon photonics is the solution to integrated optics and high-speed data communication, and the silicon modulator is one of the key devices for such applications. Intensive work to increase the bandwidth and overall efficiency of silicon modulators has been carried out in recent years. Carrier depletion-based structures using reverse-biased pn or pin diodes are the most used to achieve high-speed and reliable refractive index variation in silicon. The junctions of these devices are usually designed parallel to the direction of light propagation in either vertical of lateral configurations. However, using this design, the modulator is limited by space charge extension, and a trade-off is obtained between modulation efficiency, speed, , and optical loss. An alternative solution to such limitations is to place the pn diodes orthogonally to the direction of light propagation so that the optical mode propagates throughout successive depleted regions, maximizing the interaction between the light and the regions where the refractive index variation occurs .

We present experimental results of a high-speed silicon optical modulator based on carrier depletion in interleaved pn junctions oriented in the waveguide direction. The modulator is integrated in a ring resonator of radius 50 µm. The modulator is characterized using a laser beam at 1.55 µm for TE and TM polarizations and extinction ratios (ER) as high as 11 dB in TE and 10 dB in TM polarizations are obtained between 0 and -10 V, with an insertion loss of ~6 dB. The high-speed performance of the modulator was determined with optical eye diagrams. At 10 Gbit/s, it provides an extinction ratio (ER) of 4.1 dB for TE polarization, and 2.8 dB for TM polarization.

8431-19, Session 5

Slow light-enhanced carrier depletion modulators with 1V drive voltage

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Slow light optical modulators are attracting ever more attention in the field of silicon photonics owing to their capacity to shrink the footprint of conventional rib waveguide based carrier depletion modulators while maintaining similar drive voltages. Nonetheless, the integration of future photonic components with advanced complementary-metal-oxide-semiconductor (CMOS) electronics will require drive voltages as low as 1V. Here, we demonstrate that the use of slow light provide an attractive solution to reduce the driving power of carrier depletion-based Mach-Zehnder modulators so that they are one step closer towards fulfilling the consumption requirements of future CMOS electro-photonics transceivers.The device combines the attractive properties of slow light propagation in a nanostructured periodic waveguide together with a high speed semiconductor pn diode.Preliminary characterization results show that our 1mm-long slow light device features a data transmission rate of 5 Gbit/s with ~5.7 dB extinction ratio under a 1V drive voltage.

8431-20, Session 5

Strain tuning of Ge electro-absorption modulators for Si photonics

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Recently, there have been great progresses in Si-CMOS compatible Franz-Keldysh Ge-based electro-absorption (EA) modulator because of its micrometer footprints, low power consumption (10 - 100 fJ per bit) and operation wavelength around 1.55 um. The challenge is its narrow operation window ~0.015 um, and thus we need several compositions of SiGe alloys for the modulation to cover the whole C+L band (1.53 - 1.62 um). The present paper proposes a new approach to tune the bandgap of Ge with various strains to cover the whole range.

We employed SiNx as stressors, and measured the induced strain in Ge with SiNx by microscopic Raman spectroscopy. We also measured the photocurrent spectra of Ge photodetectors on Si. 400 nm thick Ge epilayers were grown on 4-inch p+ Si(100) substrate by ultra high vacuum chemical vapor deposition (UHV-CVD). Then, phosphorus donors were implanted to make vertical p-i-n diode structures. The phosphorus peak concentration was approximately 10^20 cm-3. Finally, 500 nm thick SiNx films were deposited, patterned, and etched to make stressor stripes on Ge photodetectors, with Al metallization.

Raman spectroscopy has revealed the presence of ~200 MPa of tensile stress in Ge below SiNx stressors. The k p theory predicted the absorption edge of Ge with stressors should shift by an amount of 0.02 um to the longer wavelength. Our free-space Ge photodetectors on Si with SiNx stressors show the predicted red-shift, compared to those without the stressors.

The proposed strain-tuning method only requires one-time Ge epigrowth, and the operation wavelength is to cover the whole C+L band depending on the SiNx stressor deposited in the backend process. This could lead a new concept of modulator in Si photonics; “field programmable modulator array”.

8431-21, Session 5

The effects of strain on indirect absorption in Ge/SiGe quantum wells

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In III-V materials systems the dominant technology for optical modulation is the quantum-confined Stark effect (QCSE), which can be exploited either in electroabsorption or Mach-Zehnder interferometer (MZI) devices. In 2005 the QCSE was first demonstrated in Ge/SiGe quantum wells, which were epitaxially grown on a silicon substrate, and in the following years considerable progress has been made in characterising the electroabsorption properties of these quantum well systems.

The fundamental limitation for the extinction ratio and insertion loss that can be achieved using Ge/SiGe quantum well stacks comes from indirect absorption, which results from rapid intervalley phonon scattering processes. However, to date a systematic investigation of the factors that contribute to indirect absorption has not been carried out.

We calculate the electronic band structure at the Brillouin zone centre, as well as the X and L points, and use this to calculate the carrier dynamics in Ge/SiGe quantum wells to determine the strain dependence of the carrier lifetimes. We find that the energy of the X-valleys is important in determining the amount of indirect absorption, and consequently that indirect absorption is strongly related to the substrate strain.

We grew and characterised highly-strained Ge/SiGe devices with systematically-varied dimensions, which exhibit modulation of the absorption coefficient at and around 1.3 um. Comparing this data with our calculations allows us to draw conclusions about the carrier dynamics, and how the alloy composition and substrate strain affect the limits of performance in Ge/SiGe quantum well modulator devices.

8431-22, Session 5

Electroabsorption based on quantum-confined Stark effect from Ge/SiGe multiple quantum wells

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Strong light modulation based on the quantum-confined Stark effect (QCSE) from Ge/SiGe multiple quantum wells (MQWs) grown by low-energy plasma-enhanced chemical vapor deposition (LEPECVD) is studied at room temperature. Three different device configurations based on Ge/SiGe MQWs are employed: a surface illuminated diode, a 100 µm wide planar waveguide, and a 3 µm wide waveguide. Firstly, optical transmission, photocurrent, and differential transmission measurements were used to characterize absorption spectra of the MQWs as a function of the applied electrical field in terms of the absorption per well with light incident vertically to the diode surface. Next, electroabsorption was demonstrated with light incident parallel to the plane of the quantum wells in a planar waveguide structure. Strong polarization dependence of two transitions: the top of the heavy-hole valence band (HH1) and the tops of light-hole valence band (LH1) to the bottom of the conduction

band at zone centre will be presented, and it will be shown that significant light modulation can be obtained with device length varying from 34 to 114 µm. Finally, modulation characteristics including extinction ratio and large modulation bandwidth of a 3 µm wide and 100-150 µm long waveguides based on Ge/SiGe MQWs will be demonstrated.

8431-23, Session 6

Real-time and low-cost biosensors based on photonic bandgap structures

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Planar photonic structures are envisaged as a highly promising candidate for the development of label-free biosensors on which future lab-on-a-chip (LoC) devices will be based. These structures present several advantages compared to other sensing technologies such as high sensitivity, compactness, the possibility for multianalyte detection, label-free detection, and cost reduction when using CMOS-compatible fabrication techniques.

However, photonic biosensors most commonly used nowadays rely on the spectral shift of their characteristic response when changes in the refractive index of the surrounding medium are produced, as occurs when using ring resonators or photonic crystals. The main limitation of these biosensing systems is the need for the continuous acquisition of the transmission spectrum of the structure, for which either a tunable laser or a spectrum analyzer is needed. These elements are costly and require several seconds or even minutes to obtain the desired spectrum.

We propose a novel technique for the development of real-time and low-cost integrated photonic sensing devices where photonic bandgap (PBG) structures are used to perform the detection. Instead of using expensive tunable elements, the PBG shift is indirectly tracked by exciting the structure with a filtered broadband source and measuring the output power with a simple power meter. When the PBG edge of the structure is located within the excitation wavelength range, the output power is given by the overlap between the source spectrum and the transmission band of the PBG structure. Any shift of the PBG position produces an output power variation, which allows us to perform the sensing.

We have used this technique for the detection of refractive index variations, showing high sensitivities and low detection limits, which demonstrate its high potential for the development of low-cost and real-time photonic biosensors.

8431-24, Session 6

Silicon biosensors for point-of-care diagnostic

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Point-of-care (POC) diagnostics are based on miniaturised devices in which all functionalities are integrated, from sample to signal delivery. Such a device could contain enough hard wired intelligence and robustness to be used by the patient and deliver a multitude of data to a central database. It is clear that application of a portable, easy-to-use and highly sensitive POC platform for real-time diagnosis could offer significant advantages over current methods. But despite remarkable progress towards POC clinical assay systems, very few complete working prototypes have emerged. Most of the POC technology does not incorporate on-chip detection and the read-out must be done with complex scanners in laboratory settings. Incorporation of the "on-chip" detection by using nanobiosensors is a new technology that shows great promise.

Silicon photonic biosensors based on evanescent wave detection have revealed themselves as the most promise candidates for achieving truly point-of-care devices. Advantages as miniaturization, extreme sensitivity, robustness, reliability, potential for multiplexing and mass production at low cost can be offered. Our approach based on using optimized silicon-based nanophotonic waveguides in a novel interferometric configuration promises to improve the current systems best-in-class performance for label-free biosensing incorporated in a LOC platform .

The LOC biosensor is being assembled by integrating the following part: i) novel bimodal waveguide nanosensors in a multiplexed configuration , ii) a polymer flow cell and the flow delivery system (microfluidics), iii) the light sources, photodetectors and nanometric diffraction gratings for in- and out-coupling of the light, iv) robust immobilisation and regeneration protocols for the biological receptor; v) processing electronics, and vi) final packaging and control software.

The micro/nanointerferometric devices have shown sensitivity close to 10-7 in refractive index units, which means an ability to discern, in a label-free scheme, concentrations of biological molecules at pM level. The degree of development of the individual components of the LOC device and the integration in a final prototype for extremely sensitive label-free detection of clinical samples will be presented.

8431-25, Session 6

CMOS photonics for optical manipulation of particles and biosensing

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The fusion of photonics and fluidics has over the past few years led to the nascent research area of optofluidics, which shows promise for lab-on-a-chip applications. Planar Complementary Metal-Oxide-Semiconductor (CMOS) photonic devices embedded in microfluidic channels on a silicon chip constitute the platform for CMOS optofluidics. The near field of the high-index-contrast silicon photonic waveguides, with the key advantages of surface localized fields in compact footprints and strong intensity gradients normal to the surface, can be leveraged to optically trap and route small dielectric particles in colloidal solution that are in close proximity to the waveguide surface. In order to further enhance the optical field and enrich the functionalities for optical manipulation of particles, various research groups have recently proposed and demonstrated microresonator and nanoresonator-based optical manipulation, in which the particles are manipulated using the resonance-enhanced surface wave. Such a resonance-enhanced optical manipulation is highly wavelength dependent and thus enables wavelength-tunable particle trapping and routing.

In this paper, we will review the latest progress in our work on using a host of CMOS photonic devices on silicon-nitride (SiN)-on-silica substrates for near-field-based optical manipulation of dielectric microparticles and submicrometer particles in a microfluidic channel. The SiN-based devices enable the use of visible and near-infrared light for both optical manipulation and possibly biosensing. In our current work, we employ a continuous-wave 1550nm wavelength-tunable laser light amplified by an erbium-doped fiber amplifier as a moderate-power (100mW-range output power) light source for optical manipulation. Our demonstrated optical manipulation devices to-date, all fabricated by i-line photolithography and dry-etching, include microring resonator-based particle add-drop filters and microdisk resonator-based particle buffers with multiple tracks and extended trapping ranges. Our current work emphasizes on the experiments and numerical modeling of multimode interference (MMI)-based particle splitters and waveguide directional coupler-based particle couplers. We will report our latest results on splitting and directionally coupling polystyrene particles that are optically streamed into the device in an essentially static microfluidic channel. Our preliminary results suggest that the particle splitting and coupling are wavelength tunable and appear to follow the optical mode-field distributions. However, detailed modeling of the potential energy distributions on the microparticles according to Maxwell stress tensor calculations and the numerically calculated mode-field distributions are needed in order to better interpret the experimental observations. Based on our numerical modeling and experimental results, we will also discuss promising potentials of integration of the demonstrated particle devices to form CMOS optofluidic particle circuits for more sophisticated particle manipulation and biosensing.

8431-26, Session 6

Pathogen detection system based on CMOS photonics

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CMOS photonics benefit from the unique material properties of silicon and its mature fabrication technologies. Complex photonic circuits with high component density and multiple functionalities can be made with high yield and low cost. As the research develops, CMOS photonics is penetrating into other areas of applications outside of communications and biological sensing is a field where this technology brings unique advantages. In this presentation, these advantages are reviewed and a fully integrated pathogen detection system based on silicon photonic components and on-chip microfluidics is described.

Pathogens are continuously present in our environment and are a major cause of illness in humans. It is vitally important to detect their presence at an early stage and obtain results quickly at the source of potential contaminants. The identity of pathogens can be determined through their genomic finger prints or by their selective interaction with proteins and other biomarkers. Label-free sensors provide fast results, but traditional label-free sensing systems are limited by their relatively large size, high cost and restricted multiplexing abilities.

Label-free sensors made of silicon photonic wires are highly sensitive transducers to surface adsorptions, capable of resolving surface mass changes of <0.2 pg/mm2. Due to the compact footprint, arrays containing more than 100 resonator sensing elements are contained within an area of 2×2 mm2. Noise from temperature variations are removed using on-chip thermometers. Subwavelength grating couplers are used to enable easy coupling of light into and out of the sensor chip. Analyte fluid is delivered to the sensing surface through microfluidic channels fabricated monolithically on the chip. Using these integrated optics technologies, a compact reader system with disposable sensor chips are realized. By simultaneously monitoring the interaction of bacteria such as E. coli bacteria to multiple antibody probes, the pathogenic strains are identified.

8431-27, Session 6

On-chip multiplexing concept for silicon photonic MZI biosensor array

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We present a novel on-chip wavelength division multiplexing concept for an integrated label-free biosensor array employing silicon photonic Mach-Zehnder interferometers as sensing elements. Microring resonators act as wavelength selective components in the near infrared wavelength region. The radii of the microring resonators are designed such that their resonance wavelengths are allocated equally within the free spectral range. By choosing a wavelength where a certain microring is in resonance an individual interferometer is addressed. Wire Bragg gratings terminate the interferometer arms and reflect the light back. The same ring resonator, which dropped the light couples the light back into the input waveguide, where it propagates in opposite direction. A standard fiber optic circulator between the tunable laser source and the in/output separates the incoming from the outgoing light. This concept eliminates the risk of a wavelength mismatch between drop and add port. Moreover, it minimizes alignment efforts because input and output are performed via the same coupler. In this work, the characteristics of the entire device are discussed. The design of the nanophotonic key components (micro ring resonators, Mach-Zehnder interferometers and photonic wire Bragg gratings) based on FEM and 3D-FDTD simulations as well as measurements of the spectral characteristics of the fabricated components are presented. Different to most other demonstrations the devices are designed for TM like polarization, which provides higher sensitivity for surface sensing. All structures except for the sensing arm of the MZIs are covered by an SU-8 cladding. Measurements of combinations of the wire Bragg gratings with ring resonators and Mach-Zehnder interferometer sensors demonstrate the applicability of the reflectors in photonic circuits.

Finally, as a proof-of-concept we successfully performed homogeneous sensing experiments with fluids of different refractive indices on a three-channel array employing the proposed wavelength multiplexing concept. We expect that this scheme can be extended to about 10 channels.

8431-28, Session 7

A study of variations in the free carrier absorption eect as a function of CMOS technological node

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By implementing a well-based or a diffusion-based pn-junction in standard CMOS it is possible to create an optical modulator. The lynchpin of the optical modulation is the variation of the depletion region width of the active pn-junction as a function of applied bias voltage: higher reverse bias voltage implies a wider depletion region and hence fewer free carriers to impinge upon the integrity of the test beam. This may be used to perform AM on a test electro-magnetic beam of appropriate wavelength traversing the die. Despite the fact that this simple test bench is a far cry from the intricate waveguide-based silicon photonic devices that abound in the literature, the principle of using free-carrier absorption to perform modulation on an EM beam stays the same. For that reason testing homologous structures that are fabricable in different technologies (e.g. a 0.35um n-well to substrate junction vs a 0.18um one) with the exact same test pattern (incident beam wavelength and intensity, photodetector type and operating conditions etc. all kept the same) should be able to reveal how the technological node influences the properties of the various pn-junctions used, at least qualitatively. More specifically doping concetration is expected to be highly affected by the choice of technological node in any CMOS pn-junction and that alone shall strongly impact the intensity of the free-carrier absorption phenomenon. Other important factors that affect the efficiency of the phenomenon are: geometry, the orientation of the modulator vs the EM beam, the precise doping profile function of the modulating junction (particularly in the vicinity of the metallurgical point) and the bias voltage applied at the said junction. Geometry and the orientation of the modulator vs the test beam are strongly interlinked since by appropriate layout one can either gear large optical devices (order of hundreds of squared microns) towards a predominance of horizontal (a.k.a. 'base') junctions, or vertical ones (a.k.a. 'side-wall' type). Bias voltage also plays an important role because the choice of HI and LOW voltages in a digital context will affect the contrast between a detected beam carrying a '0' and one carrying a '1'. Throughout this research we provide data gathered from 3 ICs fabricated in 0.35um, 0.18um and 0.13um respectively.

8431-29, Session 7

CMOS-compatible electro-optical Mach-Zehnder modulator based on the amorphous silicon technology

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In this contribution we report the first device based on the free-carrier plasma dispersion effect wherein the phase shift element of a Mach-

Zehnder interferometer (MZI) is an optimized p-i-n diode embedded in an a-Si:H rib waveguides. By reverse biasing the device, we induce a very fast charge modulation that, in turn, modifies the refractive index profile of the waveguide and therefore the optical phase of the 1.55 um wavelength light passing through it.

The device consists of 6 um input rib-waveguide that is in-tapered over a distance of 1 mm to a 4 um rib single-mode, birefringence free, waveguide. The tapered waveguide improves the input coupling lowering propagation and insertion losses. Input-output S-bent curved waveguides, 2050 um-long, were used to split and combine the optical beam. The S-bent radius of curvature and the intersecting angle of 1.4° result from parametrical optical simulation in order to achieve a trade-off between the need for a compact device and low insertion losses. The distance between the two parallel waveguides, 1.3 cm-long, is 50 um while the overall device length is about 1.86 cm.

The cross-section of the MZI consists of a p-i-n rib waveguide made of a 2 um-thick a-Si:H undoped core region between a p-doped a-SiC:H bottom cladding (2 um-thick) and an n-doped a-SiC:H top layer (300 nm-thick). These layers were fabricated on a doped c-Si substrate by Plasma Enhanced Chemical Vapour Deposition (PECVD) at low temperature (TMAX=170°C) to ensure an easy back-end integration with CMOS. The W=4 um-wide rib waveguides were patterned by photolithography and etched to a depth of 520 nm by a reactive ion etching (RIE). One arm of the MZ modulator was covered by a 100 nm-thick evaporated aluminum film to ensure a good ohmic contact.

We have tested the behavior of the waveguide-integrated MZI by performing both DC and AC measurements. Light intensity is modulated by the phase shift induced in one arm of the interferometer by free carrier depletion in the p-i-n junction. The optical transmission of the MZI was scanned over a wavelength range of 2 nm between 1549 nm and 1551 nm. At each wavelength, a DC reverse bias between 0 V and 60 V, in steps of 1 V, was applied to the phase shifter between the top Al contact and the substrate. We measured modulation depths as high as 14%. The figure of merit Vpi·Lpi (the voltage required to achieve a pi phase shift for a given length) was extracted from the transmission vs. reverse voltage plot. We calculated a static Vpi·Lpi product of ~40 V·cm. The on-chip insertion loss was ~18±1 dB when the MZI is in the “ON” state. We also measured the fiber-to-fiber losses of a straight p-i-n rib waveguide (W= 4 um) to evaluate the propagation losses, estimating a value of about 4.3±0.2 dB/cm. The speed performance of the reported vertical p-i-n depletion modulator was analyzed by applying to one arm of the MZI a pulsed signal with frequency f =10 MHz, rise (fall) time of 2 ns, and adjustable peak amplitude Vp. The measured rise and fall times are ~2.3 ns, a result which excludes the potential impact of thermo-optic effects on our experiments. To our knowledge, this is the fastest electro-optical modulation ever reported in as-deposited a-Si:H-based photonic devices.

8431-30, Session 7

High-speed silicon optical modulator based on a pin diode

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Silicon photonics has generated an increasing interest in the recent years, as it can revolutionize global data communication. The silicon modulator is one of the main challenging building blocks to achieve high performance data links. Among the possibilities to achieve optical modulation in silicon-based materials, the free-carrier concentration variation has been largely used for fast modulators integrated in silicon waveguides using either carrier injection or depletion in pn, or pin diodes, or carrier accumulation in metal-oxide-semiconductor (MOS) capacitors.

We present experimental results of a high-speed silicon optical modulator based on carrier depletion in a lateral pipin diode. The purpose of adding an additional p-doped slit inside the intrinsic region of the pin diode is to reach the best trade-off between the effective index variation achieved by depletion of holes located in the middle of the waveguide, and the optical loss which is reduced as a large part of the waveguide is non-intentionally doped. The pipin diode is integrated in both arms of a Match-Zehnder Interferometer (MZI) though only one arm is biased. The design of the phase shifter is 1.8 mm-long to achieve high-data rate, i.e. to avoid RF signal propagation loss and to reduce the speed difference between the electrical and the optical signals. The modulator is characterized using a linearly TE-polarized laser beam at 1.55 µm. The maximum value of the transmission is -4 dB. The high-speed performance of the modulator was determined with optical eye diagrams. At 10 Gbit/s, it provides a large extinction ratio (ER) of 8.1 dB, simultaneously with a low optical loss of 6 dB.

8431-31, Session 7

Low-voltage high-speed Si Mach-Zehnder optical modulator with multicascade p/n junctions along waveguides

R. Furutani, Hiroshima Univ. (Japan)

Si ring light modulators are extensively studied for the on-chip optical interconnection (Amemiya et al. Jpn. J. Appl. Phys 50, 2011, 04DG13). However, there are problems such as instability against temperature change and scattering of resonance wavelengths. In order to avoid these problems, Si Mach-Zehnder Interferrometer (MZI) light modulators are studied.

This paper describes the simulation results of Si MZI modulators with multi-cascade p/n junctions along waveguides. Liu et al. reported the MZI modulator where a p/n junction is arranged in the vertical direction against the waveguide (Optics Express, 15, 2007 p. 660), and operation speed is 20 GHz. On the other hand Brimont et al. horizontally arranged the p/n junction (14th Euro Optics Conf. Netherlands 2008, p. 321). In these structures the applied voltage expands the depletion region of only one p/n junction existing in the waveguide. On the other hand in our proposed structure the applied voltage expands the depletion regions of two p/n junctions existing on the both sides of p (or n) region. Therefore, our device operates at low voltages. The length of p or n region is relatively widely designed and the doping concentration can be reduced because it is arranged along the long waveguides. The reduced doping concentration increases the operation speed because the junction capacitance is reduced. The Bragg reflection can be avoided by suitably selecting the operation wavelength and by nonperiodic arrangement of p/n junctions.

From the simulation, it is shown that the operation voltage is 1.5 V for the arm length of 5 mm at 95 percent modulation when the p (or n) region length is 300 nm. And the operation speed is 3 GHz at doping concentration of p and n region is 1.5e17/cm3. The operation speed is 20 GHz for the arm length 3 mm when the p (or n) region length is 600 nm at doping concentration of p and n region is 5e17/cm3, and operation voltage is 8 V.

The devices are now under fabrication and the measurement results will be presented at the conference.

8431-32, Session 8

Silicon photonics for optical interconnects in computing applications

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No abstract available

8431-33, Session 8

Silicon photonics at ST

G. Chiaretti, STMicroelectronics (Italy)

No abstract available

8431-34, Session 8

Opportunities and challenges of silicon photonics in optical networks

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Silicon Photonics will play a fundamental role in the future of optical networks because it will allow costs, size, power consumption to be significantly decreased, while simplifying the design because of a reduced number of interconnections, increasing functionalities and capacity. The first integrated photonics technologies emerged recently for application in optical communications are either based on co-integration of InP photonics with Silicon-based electronics or, instead, based on co-integration of both photonics and electronic circuits on Silicon substrates. Among the others Silicon Photonics is the most promising due to the use of largely diffused CMOS production infrastructure that can guarantee a high yield with respect to the InP one, but key challenges must be addressed concerning performance. The presentation will review new approaches in solving some of the most critical aspects of Silicon Photonics, such as i) integration of III-V substrate (needed to realize laser sources) on Silicon, ii) efficient coupling Silicon nano-structure to optical fiber, iii) low-cost co-integration of photonic and electronic circuits. Finally, key relevant application of Silicon Photonic devices in optical networks will be discussed.

8431-35, Session 8

Silicon photonic, a technology for long haul WDM systems with high potential

G. Charlet, Alcatel-Lucent (France)

No abstract available

8431-36, Session 9

Photonics-electronics Integration on CMOS

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Silicon photonics has generated an outstanding interest for optical communications and for inter and intra-chip interconnects in electronic systems. High performance generic building blocks that can be used for a broad range of applications have already been demonstrated such as waveguides, I/O couplers, laser sources by III-V/Si heterogeneous integration, fast silicon modulators and germanium photodetectors. We will also review the different scenarios for integrating photonic functions with an electronic circuit, as well as the associated design, test and packaging challenges.

8431-37, Session 9

Si photonics toward WDM implementation on a chip

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Si photonics has been a power leader to make Si electronic green as well as fast. It has so far experienced to a couple of breakthroughs since his proposal by Soref, starting from Ge photodetectors, Si modulators, and ending up with Ge lasers on the Si platform. Together with development of low loss high index waveguides, these prototypes open up the way for photonic integration of circuits on Si LSIs. The on-chip WDM is Holy Grail since it enhanced information capacity by at least a couple of orders magnitude. The “last one mile” is locking wavelength (λ) on an uncooled LSI chip. Some specification requires the chip to work, say 100 ˚C. The “uncooled” architecture severely limits the channel density on chip WDM, since dn/dT of Si is 2e-4/˚C, where n denotes refractive index, and T temperature. This leads dλ/dT ~ 0.1 nm, and thus shift 10nm under the chip specification above. Therefore, the WDM channel number may be less than 10 in the C+L band (1.53 - 1.62 µm). The present paper proposes a stress tuning the wavelength to lock wavelength.

We have prototyped Si beam structure on SOI by MEMS and tuned the bandgap by internal strain by external force, here mechanical force. The deformation potential calculation indicates the Si bandgap should shrink by ~0.1 eV under 1 % tensile strain, which we verified experimentally. This means Si can detect 1310 nm light under the strain. We could simultaneously control refractive index of Si. We also report stress dependent behaviors of the other beam materials such as Ge and GaAs. The proposed strain-tuning of optical properties of various semiconductors is powerful to precise control of the complex refractive index for λ locking against temperature fluctuation of chip temporally and locally.

8431-39, Session 9

Co-integration of Ge detectors and Si modulators in an advanced Si photonics platform

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A Si photonics platform is described, co-integrating Ge photo-detectors with carrier depletion and accumulation type Si-modulators and with other advanced passive photonics components. This platform is developed on a 200mm wafer-size CMOS compatible toolset, as used by a 130nm-node CMOS baseline.

The advanced passive component modules use an oxide/poly-Si stack on top of a 220nm thick SOI layer with a 2µm thick buried oxide. Using 193nm lithography this stack is patterned using 4 litho levels. Dopants are introduced in the Si using low dose and high dose n- and p-type implantations, with phosphorous and boron respectively, to form depletion Si modulators. After the implants, an oxide cladding layer is deposited, which is planarized using chemical mechanical polishing (CMP), exposing the poly-Si stack. The poly-Si stack is subsequently implanted and annealed, to enable carrier accumulation type modulators.

The Ge detectors are then fabricated using Ge selective epitaxial growth in oxide trenches created on top of the Si structures. A high degree of Ge relaxation is obtained by growing thick layers (2µm), and using a post deposition anneal. Threading dislocations move through the Ge during this process, and terminate at the Ge/Oxide interfaces. In this way, the impact of the threading dislocations on the dark current of the detector can be engineered. Subsequently, a Ge CMP selective towards the underlying oxide is used to obtain a flat surface. At this point a Si1-xGex cap layer is selectively grown to allow for a bigger process window for the reaction with Ni. After n- and p- type implants, a local and simultaneous Ni silicidation and silico-germanidation scheme was used, providing for a good electrical contact. The back-end includes W plugs and a Cu metallization.

Using this flow, both Ge detectors and Si modulators were successfully co-fabricated. The Ge detectors demonstrated a responsivity of 0.5 A/W for a dark current of less than 7 µA. Optimisation of the Ge material quality and implantations can further reduce the dark current of these detectors. Both accumulation and depletion type ring modulators were also fabricated. The accumulation type modulators reached extinction ratios of 7dB at insertion loss of 5 dB for 1V peak-to-peak swing with >1Gb/s operation. Depletion ring modulators reached speeds of 10 Gb/s, at an extinction ratio of 4 dB and an insertion loss of 6 dB for 1 V peak-to-peak swing.

These results demonstrate the successful integration of passive and active photonics components in a CMOS compatible flow.

8431-40, Session 9

New integration concept of PIN photodiodes in 0.35um CMOS technologies

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We report on a new and very cost effective way to integrate PIN photo detectors into a standard CMOS process.

Starting with lowly p-doped (intrinsic) EPI we need just one additional mask and ion implantation in order to provide doping concentrations very similar to standard CMOS substrates to areas outside the photoactive regions. Thus full functionality of the standard CMOS logic can be guaranteed while the photo detectors highly benefit from the low doping concentrations of the intrinsic EPI. The major advantage of this integration concept is that complete modularity of the CMOS process remains untouched by the implementation of PIN photodiodes. Implant conditions for the additional ion implantation were first determined by TCAD process simulations and finally proved by spreading resistance measurements on the appropriate wafer areas. Functionality of the implanted region as host of logic components was confirmed by electrical measurements of relevant standard transistor as well as ESD protection devices.

We also succeeded in establishing an EPI deposition process in our FAB which guarantees the formation of very lowly p-doped intrinsic layers, which major semiconductor vendors could not provide. With our EPI deposition process we acquire doping levels as low as 1E12/cm^3. In order to maintain those doping levels during CMOS processing we employed special surface protection techniques. After complete CMOS processing doping concentrations were about 4E13/cm^3 at the EPI surface and reached the original lower doping concentrations at depths of about 2-3µm.

Photodiode parameters could further be improved by bottom antireflective coatings and a special implant to reduce dark currents. For 100x100µm^2 photodiodes in 20µm thick intrinsic EPI on highly p-doped substrates we achieved responsivities of 0.57A/W at l=675nm, capacitances of 0.066pF and dark currents of 0.8pA at 2V reverse voltage. These values are substantially better than those of previously reported devices [1].

[1] A. Marchlewski, et al., “Universal PIN Photodiodes in a 0.35µm BiCMOS Mixed Signal ASIC Technology”, Proc. SPIE, Vol. 7220, 72200C (2009).

8431-78, Session 9

Silicon as a platform for quantum photonics

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Quantum information technologies offer completely new and powerful approaches to encoding, processing and transmitting information. By harnessing the properties of quantum mechanics, such as superposition and entanglement, it has been shown possible to realise fundamentally new modes of computation, simulation and communication, as well as enhanced measurements and sensing. Of the many prospective physical systems in which to encode quantum information, photons are a particularly promising approach due to their properties of low noise, easy of manipulation and low transmission losses. To-date, quantum photonic integrated circuits have been realised in low-index-contrast waveguide material systems, such as silica-on-silicon and silicon-oxy-nitride. Such technologies offer benefits in terms of low propagation losses, but their associated large bend radii limits the scalability and usefulness of this technology.

Here we present a quantum technology platform utilising the silicon-on-insulator material system, where quantum interference and the manipulation of quantum states of light is demonstrated in components two-orders of magnitude smaller than pervious implementations. Quantum interference of indistinguishable photons is demonstrated in a multi-mode interference coupler with a raw visibility of 80%, and quantum enhanced phase resolution of a Mach-Zehnder interferometer is presented with 89% fringe contrast.

In addition, we demonstrate on chip photon pair generation in ring resonators sources with a footprint of ~100um2. The photons are generated using four wave mixing enhanced by the high confinement of light in the silicon nanowire. This source generates photon pairs in well defined side bands shaped by the ring response and exhibits coincidences to accidental ratio as high as 460.

These technologies pave the way towards a fully integrated platform for quantum technologies where the photon sources, circuits and detectors can all be integrated onto the same chip to provide applications in quantum communication, simulations and computation.

8431-41, Session 10

Er- and Nd-implanted MOS light emitting devices and their use for integrated photonic applications

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In the past, the suitability of Er for Si-based light emission was already investigated in detail. However, much less attention has been paid to Nd with its main electroluminescence (EL) line around 900 nm. In this study we compare the electrical and EL properties of Er- and Nd-implanted MOS structures where the dielectric stack is composed of the implanted SiO2 layer and a SiON buffer layer. Regarding the EL, the EL spectrum, the EL decay time and the EL efficiency were measured. The electrical characterization comprises IV measurements, charge-to-breakdown measurements and first results regarding the comparison between AC and DC operation. Although the EL efficiency of Nd-implanted devices is by a factor of 5 to 10 lower than that of Er-based, the emission wavelength of Nd has some advantages compared to that of Er. Finally, based on these results the suitability of these two types of light emitters for integrated photonic devices is discussed.

8431-42, Session 10

Carbon nanotubes for photonics: light emission in silicon and optical gain

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For several years, silicon photonics have been extensively studied to overcome the limitation of metallic interconnects in microelectronics circuits. Although silicon-on-insulator substrates allow compact photonic structure due to the high contrast between silicon and silica and low loss propagation, silicon is an indirect bandgap material with rather poor optoelectronic properties. This point leads to consider alternative materials for active devices in silicon photonics technology, and among them, carbon nanotube are a proemining candidate thanks to their ability to emit, modulate and detect light in the wavelength range of silicon transparency.

We report on the use of carbon nanotube for photonic application. First, we show how a polyfluorene assisted extraction process allow to select only semiconducting nanotubes (s-SWNT) without any traces of remaining metallic nanotubes, as confirmed by photoluminescence, absorption and Raman spectroscopies [1,2]. This leads to the first

experimental demonstration of a strong optical gain of 160 cm-1 at 1,3 µm in (8,7) s-SWNT at room temperature [3]. Special emphasis will be put on the s-SWNT extraction, as optical gain could not be achieved in a raw or lowly extracted sample, presumably due to interactions with remaining metallic nanotubes.

We will then report on the first integration of absorption and emission properties of carbon nanotubes in silicon waveguides, leading to the demonstration of the temperature independent emission up to 100°C from carbon nanotubes in silicon at a wavelength of 1.3 µm [4].

These results constitute a significant milestone towards the development of carbon nanotube based laser source, and open bright perspectives for future high performance integrated circuits.

[1] N. Izard et al., Appl. Phys. Lett. 92 (2008) 243112

[2] E. Gaufrès et al., Opt. Lett. 34 (2009) 3849

[3] E. Gaufrès et al., Appl. Phys. Lett. 96 (2010) 231105

[4] E. Gaufrès et al. submitted

8431-43, Session 10

Opto-electrical characterization of erbium-doped slot waveguides

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The convergence of photonics and microelectronics within a single chip is lacking of a reliable on-chip optical amplifier. Rare-earth doped slot waveguides show a large potential for the on-chip amplifier. These structures increase the light confinement in the active layer and can offer the possibility of electrical injection using, for example, dielectrics embedded with silicon nanocrystals. In this work slot waveguides formed by two thick silicon layers separated by a thin erbium doped silicon rich silicon oxide layer are studied. The waveguides are grown in a CMOS line with both low-pressure and plasma-enhanced chemical vapor deposition. Optical tests are performed and efficient light propagation in the slot waveguide is observed. Using the cut-back technique, propagation losses equal to 10 dB/cm are found at the wavelength of 1480 nm. The same value is found in a silicon dioxide slot waveguide doped with erbium. This high value is due to electrically conductive silicon claddings of the slot waveguide. Room temperature electroluminescence is observed at 1.54 µm and in a visible wavelength region due to the erbium transitions. The difference in the spectra of the waveguide with and without silicon nanocrystals is similar to what has already been observed in the light emitting devices with the same active material. More opto-electrical characterizations will be presented at the conference. The study of the transmitted optical signal as a function of the injected current into the waveguide will be performed, in order to see the amplification of the signal in the Er-doped slot waveguides.

8431-44, Session 10

Room temperature direct-gap electroluminescence in Ge/SiGe quantum well waveguides

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Room temperature (RT) direct gap electroluminescence (EL) from Ge/Si0.15Ge0.85 multiple quantum well (MQW) waveguides will be presented. The Ge/SiGe MQWs were grown by low-energy plasma-enhanced chemical vapor deposition (LEPECVD). P-i-n diodes embedded in 3 µm wide and 80 or 300 µm long waveguides were fabricated. RT EL spectra of the Ge/SiGe MQWs were collected from the edge of the waveguide by an objective and were recorded from 1260 to 1530 nm using a spectrometer coupled with a liquid nitrogen-cooled InGaAs detector. The electrical injection was provided by pulse forward bias with current density values varying from 2 to 7 kA/cm2. The excitonic transition between the first valence band heavy hole level (HH1) and the first conduction band state at the gamma point is clearly observed at around 1420 nm. The dependence of the EL intensity on the injection current and temperature will be demonstrated. The measured values have shown a good agreement with calculations based on the Varshni coefficient. Significantly, EL spectra at direct gap have exhibited better efficiency at higher temperature, confirming the promotion of carriers from L to gamma valley due to the heating effect, which is favorable for application in CMOS integrated circuits which normally work at high temperature. Moreover, the direct gap EL from Ge/SiGe MQWs has been shown to be transverse-electric (TE) polarized, confirming that the EL originates from recombination with a HH state. These results show that Ge/SiGe MQWs are a strong candidate for monolithically integrated light sources on the Si platform.

8431-45, Session 10

Delayed photoluminescence in three-dimensional silicon/silicon germanium nanostructures

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In three-dimensional (3D), island morphology Si/SiGe nanostructures with the enhanced local strain field visualized by transmission electron microscopy, we find unusual low temperature photoluminescence (PL) dynamics. The PL detected at 1350 nm rises practically instantly and decays exponentially with a lifetime close to 2 microseconds. In contrast, the PL detected at 1550 nm has a rise time of longer than 3-4 microseconds, and it decays with a characteristic lifetime which changes from 10 microseconds to milliseconds. The proposed model considers exciton diffusion and influence of local strain in 3D Si/SiGe nanostructures.

8431-46, Session 10

Visible light emitting Si rich Si3N4 microdisk resonators for sensoristic applications

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In the last decade a large variety of integrated photonic elements found application in the sensoristic field. Indeed, photonics plays a principal role in the realization of miniaturized, versatile and inexpensive detection systems. Different approaches of direct detection have already been reported such as Mach-Zehnder interferometers, surface plasmon resonator (SPR), photonic crystal cavities and directional couplers. Most of them can guarantee very high performances in terms of minimum detectable refractive index variation, but require a relatively large interaction length with the analyte, decreasing the compactness of the system.

On the other hand, optical µ-resonators cavities, such as disks or rings, present reasonably high sensitivities (S) up to 5 × 10^2 nanometres per refractive index unit (RIU) change, in a reduced space.

One of the main issues concerning passive µ-resonators is the need of a broad band light source (broad-band lamp or tunable laser) that has to be externally coupled into a bus waveguide. An interesting alternative to

lessen these conditions is the use of an efficient light emitting material (active material) within the μ-resonator, which can be top-pumped externally by optical or electrical means in a relaxed configuration. As an active photonic material, Silicon-rich Si3N4 (SRSN) provides several appealing properties for fabricating compact and efficient emitting devices.

In this work, we propose and characterize a basic sensing photonic structure consisting on a μ-disk cavity made of a SRSN material coupled to a passive stoichiometric Si3N4 passive waveguide placed underneath. Even though the potential sensitivity would be larger for μ-rings, we have studied μ-disks owing to the possibility of an electrical excitation without affecting the sensitive surface of the cavity.

We have been able to produce bright and high Q isolated μ-disks, achieving maximum values about 1.4x10^4 in a wide spectral range and emitting up to few nW on a single resonance. As final result, we demonstrate that the sensor can achieve a sensitivity of 36.52 nm/RIU and a minimum detection limit of 1.6 × 10^-3 RIU.

On the basis of these results, we believe that SRSN μ-disks have great potentiality to become building blocks of a photonic platform for sensing where demultiplexion and detection can be integrated on the same chip.

8431-64, Poster Session

A diode-based bolometer implemented on micromachined CMOS technology for terahertz radiation detection

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Research on terahertz sensing has produced a large number of different devices and sensing principles: schottky diodes direct detection, plasma waves with field-effect transistors, antenna-coupled microbolometers, photoconductive antennas, multiple quantum-well photodetectors, etc.

Among these solutions, bolometers proved to be a flexible option: the intrinsically large frequency operating range of the sensing principle, limited only by the antenna design, together with the possibility of integrating readout electronics brought to the first real-time imaging without scanning. However, their main limitation is the expensive production line due to the use of specific fabrication processes in addition to the regular readout electronics fabrication, bringing the cost of a device to more than twice the cost of a single CMOS chip.

In this work an antenna-coupled microbolometer based on a 0.35um CMOS technology with a low-cost maskless micromachining post-process is proposed. The device is suspended above the substrate on an oxide membrane by removing the silicon underneath with a TMAH anisotropic etching. It is composed of an antenna connected to a matched load, which heats up proportionally to the captured electromagnetic radiation, and heat sensing elements. These elements consist of several series polysilicon diodes placed near the antenna load, while an identical set of diodes is also included as a reference to track ambient temperature variations. Polysilicon diodes have been chosen instead of substrate diodes because they are located in the oxide, and the removal of the substrate preserves their functionality.

Theoretical calculations and preliminary temperature characterization of polysilicon diodes have been performed. Different antenna sizes have been used so as to obtain detectors for 0.5THz, 1.0THz, and 2.0THz frequency operation. Also, the heat sensing elements were fabricated with 2 up to 8 series diodes in order to evaluate the signal level and the expected improvement in signal-to-noise ratio. Thanks to the use of a standard CMOS technology, in the same chip a custom designed readout circuit has been integrated with the objective to maximize the performance of the detectors through signal amplification and filtering. The readout circuit features an optimized integrator to amplify the difference between active diode elements and reference elements.

8431-65, Poster Session

Arrayed waveguide gratings beyond communication: utilization of entire image-plan of output star-coupler for spectroscopy and sensing

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Although Arrayed Waveguide Gratings have been developed for multi/De-multiplexing of optical channels in the ITU grid it has not been fully exploited to use to its full capacity. One major aspect have investigated is to utilize the entire image-plane of the output Star-coupler of the AWG. If the input central wavelength, c , to the conventional AWG has been shifted by an amount, smaller than the channel spacing the new input signal, c, will be focused between the receiver waveguides at the image-plane resulting loss of data. This means a standard AWG could not be used to its full potential when the input to the AWG is a continuum of light.

A conventional Arrayed Waveguide Grating (AWG) has been tailored for non-conventional applications such as Astro-Photonics, Life Science and Spectroscopy where the input signal could be a continuum spectrum, compared to discrete optical channels in optical communication systems. The material system chosen for the AWG design is silicon-nitride/SiO2/Si (Si3N4-SiO2-Si) due to its (Si3N4) high non-linear coefficient with the absence of two-photon absorption. The choice of material system would allow us to integrate high Q-factor ring-resonators need for the generation of narrow line-width Frequency-COMBS for the realisation of calibration sources for many applications.

While existing conventional AWGs cannot be utilised in spectroscopy when the input is a continuum, due to the fixed output waveguides, the proposed new design has no output waveguides permitting to utilize the entire image-plane of the output star-coupler. In essence if the input centre wavelength c has been shifted (c) the focused spot of the input signal, (c), will be moved in the image-plane allowing to access the new focused spot through proper optics to project the entire image-plane on to a CCD array as in used in Astronomical applications. The new design could be readily employed in Astronomy or Spectroscopy for spectral slicing of photons emanating from galaxies to molecules. A continuum of spectrum can be spectrally sliced with a given resolution. The designed AWG in can slice up to 40 spectral channels with channel spacing 0.4nm (50GHz) and adjacent channel cross-talk level < -25dB at the ITU grid (25GHz) with insertion loss non-uniformity ~ 2.5dB. Image-plane is designed to be on a straight line. The device foot print is approximately 15x17 mm2 with an array of 160 waveguides. The proposed AWG-Spectrometer could easily be fabricated using standard lithography and plasma processing techniques without additional processing steps for athermalisation. However when the entire focal plane is imaged using a CCD array, it needs to calibrate accurately. Integration of ring-resonators on the same platform would enable the realisation of calibration source (Frequency-COMB based) and spectrograph on a single chip reducing the complexity and cost. Reduce cost/complexity and enhanced modularity beneficial for mass production. To our knowledge this is the first time a spectrograph has been designed on Si3N4, exposing the entire image-plane to access data, for Astro-Photonics and Spectroscopy. Integrated Photonics Spectrographs utilizing AWGs have been proposed to replace classical spectrographs for Astronomy and Spectroscopy.

8431-66, Poster Session

Simulation of polymeric integrated Young interferometer sensor

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The use of photonic integrated circuits made of polymer materials represents a solution for obtaining low-cost immunosensors for fast

clinical diagnosis. In this paper are presented the simulation studies of a photonic integrated sensor on silicon substrate based on the configuration of Young interferometer. The core and cladding materials of the photonic sensor are polymeric materials. This sensor works for the detection of the surrounding medium refractive index variation and also for the detection of a thin adsorbed layer on the sensor surface. Simulations are performed using the Beam Propagation Method for obtaining the relation between the variation of the surrounding refractive index or the presence of an adsorbed layer and the displacement of the interference fringe position. From this dependence one can calculate the sensor sensitivity and also one can estimate the detection limit. In order to obtain reliable results it is necessary to have waveguides which presents single mode operation regime both on the horizontal and vertical direction. Rib waveguides which are more prone for satisfying single mode condition were considered. The suppression of the higher order modes on the vertical direction by leakage in the silicon substrate is made by adjusting the thickness of the silicon dioxide buffer layer.

From BPM analysis it has been found that rib waveguides configured from a 600 nm thick SU8 layer (the refractive index of SU8 is 1.61 for 635 nm wavelength), having 2 microns the rib width and 50 nm rib heights exhibit single mode operation on the horizontal direction. The thickness of the silicon dioxide buffer layer is 950 nm, which is sufficient for suppression of the first order vertical mode after a relative short propagation length of 1 mm, but also prevent significant propagation losses for the fundamental mode even for 15 mm total length of the photonic circuit.

From the far-field fringe displacements obtained from simulations it has been obtained that their position shift with 118 microns if the refractive index of the analysis medium varies from 1.33 to 1.36. The sensing window length is 400 microns, the reference and sensing waveguides are placed 20 microns from each other and the distance between Young interferometer and the sensing element is 10 mm. The interfringe distance is about 315 microns.

8431-67, Poster Session

Thermal analysis on silicon photonics integrated MZI modulator and driver

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In today's market the usage of silicon photonics is very versatile. The advantages of shrinking components, and integrating optical components on a chip is be most promising and most powerful technology for faster transfer rates between and within microchips. The production of silicon photonic devices can done using well known and established semiconductor fabrication techniques. But the integration optical devices on a chip also carries problems.

The integrated SOI symmetrical MZI's can be considered wavelength insensitive providing that the performance of the splitter and combiner does not vary significantly with temperature variation. In the other hand, the draw back of the asymmetric MZI is the temperature sensitivity due the difference in arm lengths.

Optical functions that are integrated onto CMOS photonics chips may exhibit thermal sensitivity. Heat affects the performance of semiconductor devices and therefore static temperature, thermal gradient and thermal cycle's needs to be considered to satisfy the needs of reliability assessments and lifetime prediction of a product. In our work we generated a full modulator 3D model containing a driver, RF lines, the anisotropic silicon bulk material and the surfacing oxide layer. Using the FEA (Finite Element Analysis) we could show that the thermal design of the demonstrator satisfies the requirements and does not influence the optical performance of the device. In order to obtain good simulation results with FE Analysis, the boundary conditions are essential. In the given simulation we used 2 types of boundary conditions: Thermal boundary conditions and electrical boundary conditions.

The electrical boundary conditions were given by the parameters of aluminium wire and the applied voltage. The first simulation parameter is the ambient temperature. We could also show that the power dissipation along the metal lines lead to an additional transverse temperature distribution in the direction of the metal.

We also studied the impact of convection on the temperature distributions in the die.

8431-68, Poster Session

Approximate model of a DBR/F-P laser based on Raman effect in a silicon-on-insulator rib waveguide

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The stimulated Raman scattering (SRS) in silicon-on-insulator waveguides is the main nonlinear effect making this technology attractive for practical applications [1,2]. A growing interest in the SRS based lasers caused that numerous theoretical models have been proposed in literature describing this effect. However, each of them requires advanced numerical methods.

In this paper we present an approximate method of the modelling of Raman generation in silicon-on-insulator rib waveguide with DBR/F-P resonator. This method is based on an energy theorem and threshold field approximation [3]. Presented model includes, especially, nonlinear effects involved in an SOI waveguide, such as Raman amplification, two-photon absorption (TPA), free-carrier absorption (FCA), as well as self-phase-modulation (SPM) and cross-phase-modulation (XPM) (i.e. effects induced by the Kerr nonlinearity).

In our detailed theoretical model we consider the set of partial differential equations for the pump and Stokes pulses inside the laser cavity. These equations with the appropriate boundary conditions allow to obtain the exact formula describing the energy conservation theorem for analyzed laser structure. We use it as a starting point of our approximate analysis. We approximate the pump and Stokes field distributions appearing in the energy relation, and describing the operation above the threshold, by these proportional to linear field distributions existing at the threshold.

We obtain an approximate, semi-analytical expression related the pump power to the Raman output power (i.e. the output power of Stokes lasing) and system parameters. It includes the Raman gain coefficient, FCA coefficient, TPA coefficient, output mirror reflectivities for both pump and Stokes signals, as well as parameters of the rib waveguide. With this formula, we obtain laser characteristics revealing the optimal rib waveguide geometry and the optimal coupling coefficients, which provide the maximal power efficiency.

The described model does not require complicated numerical calculations and can facilitate the design of silicon Raman laser.

References:

1. S. Ding, X. Zhang, Q. Wang, F. Su, S. Li, S. Fan, S. Zhang, J. Chang, S. Wang, Y. Liu, “Theoretical models for the extracavity Raman laser with crystalline Raman medium”, Appl. Phys. B 85, 89-95 (2006)

2. F. De Leonardis, V. Dimastrodonato and V. M N Passaro, “Modelling of a DFB laser based on Raman effect in a silicon-on-insulator rib waveguide”, Semicond. Sci. Technol. 23, 064008 (2008)

3. M. Koba, P. Szczepaski: ”Approximate Analysis of nonlinear operation of square lattice photonic crystal laser”, IEEE Journal of Quantum Electronics, vol. 46 No 6, pp. 1003 - 1008 (2010)

8431-69, Poster Session

Effect of annealing treatment on Nd-SiOx thin film properties

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Compatible with the standard Si technology, Si-based material becomes a promising candidate for future optoelectronic device. In particular, Si nanoclusters (Si-nc) embedded in an insulating matrix are found to act as sensitizers of rare earth ions such as Er3+ or Nd3+ ions, whose absorption cross section is thus greatly increased by several orders of magnitude. The annealing of Si-rich SiO2 is a crucial step that dominates the Si-nc size and density as well as the SiO2 matrix quality which are some of the critical parameters to control the coupling rate between Si-nc and rare earth ions. In this study, we investigated the effect of annealing on the microstructure and the optical properties of Nd-SiOx thin films produced by magnetron co-sputtering. The films were annealed with various durations, temperatures, and heating rates using a conventional furnace and a rapid thermal annealing setup. The structure and the optical properties were investigated as a function of these annealing parameters by means of FTIR, ellipsometry, Raman, and photoluminescence spectroscopy. The goal of this work is to further explore the relation between the structure and the optical properties in order to maximize the Nd3+ emission through an optimization of Si:Nd coupling.

8431-70, Poster Session

Quantum well intermixing in AlInGaAs QW structures through the interdiffusion of group III atoms

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The selective quantum well intermixing (QWI) technique is one promising post-growth approach to engineer the bandgap and has been reported as a means to achieve monolithic integration of different optoelectronic functions. We have reported the bandgap blue shift in AlInGaAs-based multiple quantum wells (MQW) laser structures by depositing a SiNx dielectric capping layer followed by rapid thermal annealing (RTA). In this paper, the composition profile within MQW and the diffusion of dopant are analysed by secondary ion mass spectrometry (SIMS). Based on these results, AlInGaAs single quantum well (SQW) structures with various compressively strains (CS) are then investigated and we report the enhancement of bandgap shift by increasing the compressively strain level in SQW.

From the analysis of SIMS in AlInGaAs-based MQW laser structure, it evidences that the bandgap blue shift is mainly attributed to the interdiffusion of In-Ga between QWs and barriers. After high temperature annealing, the composition ratio of Al within MQWs region is unchanged, but it seems to out diffuse close to top guiding layer. Moreover, the Zn dopant has been found to concentrate in the top of guiding region in sample with intermixing promoted, which can increase the optical loss due to intervalence absorption.

Since the bandgap shift in AlInGaAs QW is achieved through In and Ga interdiffusion, we then suggest that a higher In/Ga composition ratio in QW as opposed to the one in barrier may promote further the intermixing. To demonstrate it, several AlInGaAs compressively strained SQW structures emitting around 1530 nm wavelength embedded within lattice-matched AlInGaAs barriers are investigated. The strain level in SQW ranges from 0% to 1.2% corresponding an increase of In composition ratio from 53% to 71%. The epitaxial layers were grown on (100) semi-insulating InP substrate by metal-organic vapor phase epitaxy (MOVPE) and the active region was covered with InP layer and InGaAs top layer. A SiNx dielectric layer was then capped upon using plasma-enhanced chemical vapour deposition (PECVD), followed by RTA annealing at temperatures varying from 700˚C to 850˚C. The photoluminescence (PL) measurements were carried out using a 1042 nm-wavelength pump source to examine the bandgap shift.

The extent of bandgap shift increases generally with the annealing temperature as well as the level of compressively strain in SQW. At 850˚C annealing temperature, the PL blue shift can reach more than 110 nm for sample with 1.2%-CS SQW, but is only 35 nm with 0.4%-CS SQW.

In conclusion, the correlation of the strain in SQW and the bandgap shift indicates that the interdiffusion of group III atoms between QW and barriers can be further promoted through a design of an enlarged In to Ga composition ratio differential in SQW, which can thus lead to a more pronounced bandgap shift.

8431-71, Poster Session

Porous silicon gas-adsorption sensor structures based on the phenomena of photoluminescence and non-stationary photoconductivity

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Nowadays, control over toxic and other harmful substances in air atmosphere, water and foods is of extreme importance today. In this regards, it is intensively developed microelectronic systems for human life and health protection from hazardous gases and toxic fumes. Porous silicon (PS) is a promising material for gas sensors due to the unique combination of crystal structure and the giant surface (500 m2/cm3) what may enhance the levels of gas adsorption. Among the various sensor structures that work on the effects of change of electric conductivity, capacitance, acoustic properties of the PS it is actual sensor structures based on the photoluminescence (PL) and non-stationary photoconductivity (PC).

In this work, we carried out a study of PL in the atmosphere of various gases and calculated time relaxation dependence changes in PC which are determined by the type and concentration of adsorbed gases. It is investigated PL of PS whose pores are filled with ethanol and 10% solution of ammonia Reducing the PL intensity by 2.5 and 8 times, respectively, in comparison with that of intinial samples was observed. PL band maximum was shifted towards the short-wavelength rang by 20-30 nm for the samples with adsorbed ethanol and by 15-20 nm for the samples with adsorbed ammonia.

We have numerically investigated a relaxation model of PC of PC which takes into account photocarriers recombination on the pore surface after switching off the illumination. It has been shown that relaxation time of PC noticeably decreases with increasing the photocarrier surface recombination velocity. Since the surface photocarrier recombination velocity depends on the concentration and pressure of adsorbed gas, the established features of non-stationary photoconductivity can be used for creatiton of gas sensors based on PS.

8431-72, Poster Session

A photosensor on thin polysilicon membrane embedded in wafer level package LED

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A wafer level packaging LED with photo-sensor which is fabricated on thin poly-silicon membrane located on the corner of silicon cavity is presented in this paper.

In some fields like medical, broadcasting and photography, we require an accurate lighting. For accurate lighting, we should control the light intensity and to control the light intensity, we need to measure the intensity of a light. For such fields, we design a photo-sensor embedded in wafer level packaging LED.

Silicon wafer level packaging LED uses a silicon wafer as a substrate. We made an integrated photo-sensor for measuring the light intensity of a mounted LED on the silicon wafer substrate. The wafer substrate was fabricated with orientation silicon wafer and a cavity was etched on the top of the wafer with wet chemical anisotropic etching process for mounting a LED chip.

Because of the highly directional nature of LED illumination, a photo-sensor which is fabricated on the side of the cavity is hard to sense the light intensity of a mounted LED. So, a membrane structure photo-sensor was fabricated to sense the light of a mounted LED directly.

A thin polysilicon membrane was fabricated on the corner of the cavity. A 1µm thick polysilicon layer is used as an absorption layer and the polysilicon layer is covered with low-pressure chemical vapor deposition (LPCVD) silicon nitride layer. The silicon nitride layer is used for etch mask layer in wet chemical etching of silicon wafer. And a MSM (Metal Semiconductor Metal) type photo-sensor was fabricated on the polysilicon membrane. The device size of MSM type photo-sensor is 100X100 µm2. Ti/Al (500A/3000A) was used as the Schottky finger of a MSM photo-sensor and the finger width and space is 3 µm size. The whole process of photo-sensor fabrication and LED packaging were completed on wafer level.

The target LED chip is a white light LED chip based on a blue light LED with 450nm peak wavelength. The membrane structure photo-sensor can sense the light of the mounted LED directly, so it can measure accurate light intensity of the wafer level packing LED.

8431-73, Poster Session

Design of rare-earth doped chalcogenide microspheres for mid-IR optical amplification

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In recent years, the dielectric micro- and nano-spheres have attracted the research interest for their potential applications as distributed and low-threshold laser sources or as signal amplifiers/regenerators. Laser oscillation has been observed in a variety of rare-earth doped microspheres made of silica, phosphate, tellurite and ZBLAN glass. Chalcogenide microspheres are an attractive alternative since their high refractive index allows lower modal volume and higher absorption and emission cross sections. Moreover, their low phonon energy results in a large radiative decay rates, high quantum efficiency and it allows some radiative transitions not feasible in conventional glasses. The paper, after a brief state of the art description, illustrates the design of an Er3+-doped chalcogenide microsphere amplifier evanescently coupled with a tapered optical fiber. A refined 3D model based on coupled mode theory and solving the rate equations has been implemented in a home-made computer code. The fiber-microsphere gap, the thickness of erbium doped region, the fiber taper angle, the erbium concentration, the pump and signal powers are varied in order to identify the optimal design parameters.

8431-74, Poster Session

Laser writing of polymer 3D microstructures on the boundary of opaque-transparent substrates

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Nowadays direct laser writing in polymers based on ultra-localized photomodification is an efficient way to produce three-dimensional micro/nanostructures for diverse scientific and industrial applications. It is attractive for its flexibility to straight forwardly materialize CAD models out of wide spectrum of photosensitive transparent materials on the desired substrates/platforms. Crosslinking can be achieved by tightly focusing ultrashort laser pulses to a photo- or thermo-polymers. Selectively exposing material to a laser radiation allows creation of truly three-dimensional structures with subwavelength spatial resolution.

Precise micro/nanolithography technique known as two-photon (or multi-photon) polymerization is a modern representative of direct laser writing applying additive approach structuring. It works well for sculpting truly free dimensional objects with the resolution down to 100 nm, yet in most cases only special substrates like cover glasses are suitable for application of the method.

Here we report laser structuring results of acrylates (custom made resin AKRE), epoxies (SU-8, mr-NIL6000.3), elastomer (PDMS) and hybrid organic-inorganic materials (Ormocore b59, SZ2080) on opaque surfaces such as silicon and various metals (Au, Al, Ti, Cu, Fe). Our studies prove that one can precisely fabricate two and three-dimensional structures even on glossy (roughness RMS 0.5 µm). Using femtosecond high pulse repetition rate laser (280 fs, 200 kHz, 1030 or 515 nm), sample translation velocity can reach up to the order of 10 mm/s ensuring submicrometer structuring resolution. Furthermore, we demonstrate the ability to manufacture structures on the boundary of opaque-transparent substrates without any limitations or loss of structuring quality, thus enabling direct production of three-dimensional micro-objects on the interface of substrates having different optical, electrical and mechanical properties. It opens a way for new applications, such as three-dimensional micro-optic schemes and micro-electric circuits, incorporation of opto-fluidics and bio-fluidics.

For the realization of this approach a study on surface line thickness and material damage threshold intensity dependencies on the opaque and highly reflective substrates were performed. Within the limitation of our study experiments showed the difference of the material sensitivity comparing the most transparent (glass) to the most reflective (silicon) to be in the order of 2 times. All the other substrates had the intermediate value within this range. Additionally, tests on changing exposure conditions by varying sample translation velocity were done and showed similar results.

For the structuring of PDMS elastomer a specific mixture of photo- and thermo-initiators was experimentally derived to be the best for three-dimensional photostructuring applying tightly focused femtosecond pulses. A method of multipath scanning showed a dramatic increase of sample translation speed, thus resulting in the significant increase of overall fabrication throughput (cubic femtoliters per second at a fixed structuring resolution).

8431-75, Poster Session

Improved integrated resonators in polymer technology for tunable filter

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This paper takes place in the field of integrated optics based on polymer technology. The context is the local area and home networks, where tunable filter can give services management ability. To overcome the constraints of low cost, the technology has to be as simple as possible, with a high level of integration and with materials thermally suitable for low power consumption. In this context, integrated micro-ring resonators can provide very small size filter and thereby they have a high sensitivity to acting factors. In this study, we consider the adjustment of resonant wavelength of micro-ring by thermo-optical effect. The high absolute value of the thermo-optical coefficient of polymers, about 10-4 C-1 and their thermal properties (heat capacity and heat conductivity), become an advantage to tune the filter over a wide range of wavelength. So far, only few groups report experimental achievement of wide range tunable filters based on micro-ring resonators with this kind of materials. Recently, we reported experimental results in system at 10 Gbit/s, which show that the filter bandwidth is enough for this rate. However, some performances were not still good enough. Here, our paper present improved performances of this kind of filter based on non-standard polymers resonators with large ring radius (> 90µm that means small FSR and larger round trip) and with low energy consumption for tunable filtering. The achieved integrated polymer micro-ring filters present a high extinction ratio (between 20 to 30 dB). Then to create the thermal tunability we optimize the control by coated electrodes onto the ring area taking account of a model we develop for giving the influence of waveguide and electrodes configurations on heat distribution into the

polymer layers. Finally, the experimental results point out the suitability of this component, for tunable filtering with low electrical power control.

8431-76, Poster Session

A highly junction-capacitance-isolated 10-Gb/s CMOS optoelectronics receiver IC for short reach applications

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This paper describes a 10-Gb/s CMOS optoelectronics receiver IC for short reach applications. Many studies have been reported that can reduce the junction capacitance by using various physical methods. These efforts unfortunately increase the photodiode costs. For short reach applications such as chip-to-chip interconnect, display interconnect, optical backplane, 40GBASE-SR4 of 40G Ethernet, and 100GBASE-SR10 of 100G Ethernet, circuit techniques that can provide high-speed operation even with a large junction capacitance are required. With a second-order LC-ladder filter, we can highly isolate an inherent junction capacitance of p-i-n photodiode. The second-order LC-ladder network is adopted as an input configuration which can compensate the large junction capacitance for high-speed operation.

The receiver IC is implemented in 0.13-um CMOS technology and includes a trans-impedance amplifier and limiting amplifier. Trans-impendance amplifier consists of regulated-cascode current buffer with LC-ladder filter, trans-impedance stage, and DC-offset cancellation buffer. Transfer function of the proposed second-order LC-ladder filter has five poles and one zero. The zero frequency equals to the input pole frequency of the regulated-cascode buffer. Frequencies of five poles are located above 10 GHz, thus there is no influence on 10-Gb/s operation. By using the LC-ladder network, the receiver IC can detect 10-Gb/s optical NRZ data against 1.5 pF of large junction capacitance with considerable bandwidth enhancement compared with the conventional regulated-cascode buffer by factor of two. Additionally capacitive degeneration and inductive peaking techniques are exploited in the trans-impedance amplifier to improve bandwidth. In the limiting amplifier, active feedback amplifier with negative capacitance compensation technique is used. Four identical stages are used to achieve above 40dB of voltage gain. The fabricated IC occupies the area of 1.78mm x 1.2mm including bonding pads. The IC is measured in a full optical link with commercial VCSEL driving module. The proposed receiver IC achieves 7.9 GHz of 3-dB bandwidth with 1.5 pF of junction capacitance for 10-Gb/s operation. -17-dBm of the measured sensitivity is achieved for less than 1e-12 BER. The chip consumes only 16.5 mA of currents from a single 1.2-V supply. We believe our approach can be useful for realizing cost-effective short reach optical interconnects.

8431-77, Poster Session

A new type of sensitive semiconductor detectors of terahertz radiation

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Sensitive detectors of the terahertz radiation are required now for many applications, such as ecological monitoring of pollutants, global weather observation, laboratory molecular spectroscopy, and many others. Some of these applications - such as infrared and terahertz astronomy, one of the fastest progressing fields in modern physics - require operation in space. Construction of more advanced space-borne telescopes operating in the terahertz spectral range implies some tough and specific requirements for photodetectors used in these systems.

We propose to use narrow-gap lead telluride - based alloys heavily doped with some of the group III impurities for construction of sensitive photodetecting systems in the terahertz spectral region. Pb1-xSnxTe(In) photodetectors have a number of advantageous features that allow them to compete successfully with the existing analogs:

- Internal accumulation of the incident radiation flux,
- Possibility of effective fast quenching of an accumulated signal
- Microwave stimulation of the quantum efficiency up to 102
- Possibility of realization of a "continuous" focal-plane array
- Possibility of application of a new readout technique
- High radiation hardness

We report on the physical principles of operation of sensitive terahertz photodetectors based on Pb1-xSnxTe(In). Beside other issues, we address a direct comparison of performance of the state of the art doped Si and Ge terahertz photodetectors and their counterparts based on Pb1-xSnxTe(In) using the same cryogenics and readout electronics. The optical NEP value down to 6*10^(-20) W/Hz^(1/2) at T=1.57 K has been demonstrated at the wavelength of 350 mcm. It is shown that the spectral response of a Pb1-xSnxTe(In) photodetector spreads out at least up to 500 mcm.

These features make application of the Pb1-xSnxTe(In) photodetecting systems especially attractive for the space-borne applications, for instance, in astronomical observations.

8431-79, Poster Session

High quality factor dielectric multilayer structures fabricated by rf-sputtering

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One-dimensional (1D) Photonic bandgap (PBG) structures, can be obtained by a stack of alternating high and low refractive index dielectric layers and exhibits a frequency region of high reflectivity. [1, 2]

Oxide-based dielectric materials are particularly suitable for fabricating PBG structures because they have wide transparency from the ultraviolet to the near-infrared, and present good resistance to temperature, corrosion and radiation as well. However, accurate control of thicknesses and composition of the layers is mandatory to fabricate high quality PBG systems. Various techniques have been reported for the fabrication of microcavities based on oxide dielectric materials [1, 2, 3]. In this paper rare earth activated 1-D photonic crystals were fabricated by rf-sputtering technique. The cavity is constituted by an Er^{3+}-doped SiO_2 active layer inserted between the two Bragg reflectors consisting of ten pairs of SiO_2/TiO_2 layers. SEM microscopy is employed to put in evidence the quality of the sample, the homogeneities of the layers thicknesses and the good adhesion. NIR transmittance and variable angle reflectance spectra confirm that the presence of a stop-band from 1500 nm to 2000 nm with a cavity resonance centered at 1749 nm at 0° with a quality factor Q of about 890. The influence of the cavity on the 4I13/2 --> 4I15/2 emission band of Er^{3+} ion is also demonstrated.

[1] A. Chiasera, R. Belli, S.N.B. Bhaktha, A. Chiappini, M. Ferrari, Y. Jestin, E. Moser, G.C. Righini, and C. Tosello ,"High quality factor Er3+-activated dielectric microcavity fabricated by rf-sputtering", Applied Physics Letters 89 (2006) 171910-1 - 171910-3. DOI: 10.1063/1.2364841

[2] J. Jasieniak, C. Sada, A. Chiasera, M. Ferrari, A. Martucci, and P. Mulvaney, "Sol-gel based vertical optical microcavities with quantum dot defect layers", Advanced Functional Materials 18 (2008) pp. 3772-3779, DOI: 10.1002/adfm.200800784

[3] H. Rigneault, C. Amra, S. Robert, C. Begon, F. Lamarque, B. Jacquier, P. Moretti, A.M. Jurdyc, and A. Belarouci: Spontaneous emission into planar multi-dielectric microcavities: Theoretical and experimental analysis of rare earth ion radiations, Opt. Mat. vol. 11. pp. 167-180, 1999. DOI:10.1016/S0925-3467(98)00042-1

8431-80, Poster Session

Fabrication and characterization of silver-doped chalcogenide planar waveguides for compact nonlinear optical devices

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Chalcogenide glasses (ChGs) are emerging as an excellent platform for integrated nonlinear optical (NLO) devices, owing to their high optical Kerr nonlinearities (n2) with a sub-picosecond response time as well as low linear and nonlinear losses. Recently, around 2-4 times higher n2 has been reported by just adding a small amount of silver in ChGs without increasing two-photon absorption [1]. Wet chemical etching was a common technique in fabricating Ag-ChG waveguide because plasma etching of the material remains a rough surface covered with Ag-residues. In this work we developed a novel approach to produce Ag photo-doped As2Se3 rib-type waveguide using fluorine-based plasma and characterized its nonlinear response by employing continuous wave four-wave mixing (CW-FWM). To avoid the etch residue issue we tried to dope silver on pre-patterned As2Se3 waveguides; however, As2O3 (arsenolite) crystallites were formed on the surface as a result of oxidation of As2Se3 during light illumination for photo-doping. Thin Al2O3 layer (around 1-5 nm) coated conformally on As2Se3 guides prior to silver deposition could stop the photo-oxidation; furthermore, silver could diffuse in through this thin layer. From the depth profiling of x-ray photoelectron spectroscope we confirmed that silver content in a As2Se3 guide is uniform. FWM measurement indicated that n2 of Ag-As2Se3 is 7-10 times larger than that of As2S3, even though propagation loss of 2 micron wide guides is 10 times higher (~3 dB/cm). Nonlinear response of the guide is proportional to n2 and effective length of a device (Leff), which is determined by device length and loss. In a short device, n2 contribution is dominant over Leff; consequently, Ag-As2Se3 would be an efficient nonlinear optical material for a compact device.

[1] Keijiro Suzuki and Kazuhiko Ogusu, Opt. Express 13, 8634 (2005).

8431-81, Poster Session

Low-frequency noise and electroluminescence measurements as a faster tool to investigate the quality of monocrystalline-silicon solar cells

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The defects are the natural sources of the excess current and the excess noise and they are responsible for the changes of several measurable quantities. Physical processes in electronic devices can give a useful piece of information on the device reliability provided there is a correlation with failure mechanisms.

This paper deals with comparisons of noise spectroscopy and detection of electroluminescence noise sources in the single-silicon solar cells with diffusion of n+-emitter with the source of POCl3. The first group of samples 3121 was prepared by combination of standard washing and bath with and highly dilute HF before diffusion of n+-emitter. The second group of samples 3122 was treated only with standard washing.

The noise voltage spectral density was measured in forward biased voltage. The noise voltage being picked up across a load resistance RL=100 Ω, at a band mean frequency of 1 kHz and a bandwidth of 20 Hz.

When high electric is applied to PN junction with some technological imperfections like dislocation in PN junction or crystal-grid defect causing non-homogeneity of parameters it produces in tiny areas of enhanced impact ionization called microplasma. Microplasma produced noise, which has random spectrum in frequency range. Microplasma noise is measurable even before the creation of light emissions. Due to the comparisons microplasma detection with noise characteristic can full analyzed solar cell.

Creation of microplasma takes place at spots with non-homogeneity in structure of PN junction. Light emission is exhibited in full spectrum range. The whole process is observed with a special CCD camera in a dark special cryogenic box. CCD camera G2-3200 with low noise Kodak chip KAF-3200ME is used for measuring.

The article compares the results from noise spectroscopy, microplasma presence, defect detection by electroluminescence and effectivness Eff of solar cells. The evidence suggests that the best results are reached by a group of 3122.

8431-47, Session 11

Sol-gel thin films for photonic devices

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For the fabrication of photonic devices, the sol-gel technique is an interesting alternative to other technologies such as physical vapor deposition or chemical vapor deposition, because of potential low cost and relative ease of production.

In my research group it has been studied and developed several kind of sol-gel based materials for photonic applications. In this paper the materials developed during the last 10 years will be presented.

Highly luminescent CdSe@ZnS core-shell semiconductor quantum dots (QDs) have been incorporated in both inorganic (TiO2, ZrO2) and in hybrid organic-inorganic sol-gel matrix. Depending on QDs size, luminescent waveguides emitting from green to red have been obtained and their optical properties have been characterized. Titania based composites were seen to be inherently photo-unstable due to photoelectron injection into the bulk matrix and subsequent nanocrystal oxidation. In comparison, zirconia composites were significantly more robust with high PL retained for annealing temperatures up to 300 oC. Both titania and zirconia composite waveguides exhibited amplified stimulated emission (ASE) with one-photon optical pumping, however only zirconia based waveguides exhibited long term photostability (loss of less than 30% ASE intensity after more than 40 minutes continuous excitation).

Zirconia based films have been used for the realization of Bragg microcavities, distributed feedback lasers, and all-optical integrated micro logic gate.

8431-48, Session 11

Lithium niobate-on-insulator (LNOI): status and perspectives

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As optical components continue to replace electronics in ultrafast signal processing applications, a growing interest in further miniaturization and integration of photonic devices on a single chip is observed. Therefore, optical waveguides of high refractive index contrast of core and cladding materials are developed since a couple of years. They can have a very small cross section and also bending radius, enabling the development of ultra-compact photonic integrated devices and circuits. Silicon-On-Insulator (SOI) waveguides (“photonic wires”) and devices are the most prominent examples.

A corresponding technology for Lithium Niobate-On-Insulator (LNOI) waveguides is still in its infancy, though LN offers - in contrast to SOI - excellent electro-optic, acousto-optic, and nonlinear optical properties. Moreover, it can be easily doped with rare-earth ions to get a laser active material. Therefore, LNOI photonic wires will enable the development of a wide range of extremely compact, active integrated devices, including electro-optical modulators, tunable filters, nonlinear (periodically poled) wavelength converters, and amplifiers and lasers of different types.

The state-of-the-art of LNOI films as platform for high-density integrated optics is reviewed. Using a full-wafer technology (3” diameter), sub-micrometer thin LN films are obtained by high-dose He+ ion implantations, crystal-bonding to a low-index substrate (prefer¬ab¬¬ly SiO2) and cleaving by a special annealing step ("ion-beam-slicing"). Various LNOI structures, also combined with metallic layers, are presented. Based on such platforms, photonic wires and micro-photonic devices are developed using different micro- and nano-structuring techniques. To be specific, the fabrication and characterization of LNOI photonic wires with cross-section < 1 um2, and periodically poled LNOI photonic wires for second harmonic generation are reported in detail.

8431-49, Session 11

Progress in tunable lithium niobate photonic crystal devices

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The recent development of integrated photonic crystals within planar waveguides can help implementing compact devices with fully integrable functions. In these devices, light is confined into the crystal by a classical waveguide construction.

Lithium niobate (LN) is a suitable material for 2D photonic crystals because of its high refractive index. Moreover, it is a ferroelectric crystal of great interest to the optics, telecommunications and laser community due to its large electro-optic and non-linear coefficients and extensive applications in piezoelectric, acousto-optic, pyroelectric and photorefractive devices.

However, the realisation of high aspect ratio submicron structure in LN is up to date a challenging problem due to its well known resistivity towards standard machining techniques like wet etching.

In this seminar, I will present the design, fabrication, and optical characterisation of novel infra-red tunable lithium niobate photonic crystal devices. Slow light propagation allows enhancement of the tunability, thus, we have experimentally observed a spectacular increase on the acoustic, elecro-optic and pyroelectric properties of the nanodevices.

8431-50, Session 11

Erbium-activated silica-tin oxyde glass ceramics for photonic integrated circuits: fabrication, characterization, and assessment

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Novel materials for micro and nano-scale photonic devices have become important focuses for global photonics research and development. This interest is driven by the rapidly growing demand for broader bandwidth in optical communication networks, as well as higher connection density in the interconnection area.

Simultaneous doping of glass matrices with selected active ions can assure a broad range of wavelengths. However, the low rare-earth-ion solubility in silica glass presents a major drawback. The use of glass ceramics offers the possibility of overcoming quenching problems by dispersing the ions in a crystalline environment. Moreover, a judicious choice of the crystalline component makes crystal-ion transfers possible, thus enhancing the luminescence efficiency.

In the present work, the well-known wide band gap semiconductor SnO2 (Eg = 3.6eV at 300K) was chosen as the crystalline species and thermally created in sol-gel derived silica glass. Eu and Er-doped (100-x) SiO2 - x SnO2 glass-ceramic monoliths and planar waveguides were prepared and studied using a variety of optical and spectroscopic techniques. Raman spectroscopic measurements showed the structural evolution of the silica matrix caused by the formation and the growth of SnO2 nanocrystals. Analysis of the photoluminescence properties shows that the amount of rare-earth ions incorporated in SnO2 nanocrystals can be controlled by the SnO2 concentration. We give the spectroscopic evidence of energy transfer to rare-earth ions provided by SnO2 nanocrystals in the silica matrix. The 4I13/2 level decay curves present a double-exponential profile with two lifetimes associated with different rare-earth-ion environments.

8431-51, Session 11

Tuning the emission wavelength of semiconductor ring lasers with on-chip filtered optical feedback

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We introduce the concept of a wavelength tunable semiconductor ring laser (SRL) using on-chip filtered optical feedback. The integrated device is based on a semiconductor ring laser that can sustain lasing in two counter-propagating modes. By means of a directional coupler, part of the light emitted by the laser is coupled out to a feedback section integrated on the same chip. In the feedback section, different wavelengths are routed into separate channels using an arrayed waveguide grating (AWG). Each channels contains a semiconductor optical amplifier that can be independently biased and that works as a gate. Gates that are reversely biased or unbiased are 'closed' and absorb light whereas gates that are forward biased are open and amplify their corresponding wavelength. After being processed, all wavelengths are re-injected into the SRL by a second AWG. This configuration allows for injecting the counter-propagating modes of the SRL in their own direction. Provided the feedback phase matches the phase in the main cavity, the laser is expected to operate at the wavelength that corresponds to the biased gate. The device was fabricated in the COBRA cleanroom of Eindhoven University of Technology, using the Joint European Platform for InP-based Integrated Components and Circuits (JePPIX) that offers a set of standard photonic building blocks, showing the strength and versatility of such a generic approach to fabricate complex photonic components. Our experimental characterization of the device shows that filtered feedback can be successfully used to tune the ring laser to the desired wavelength. The filtered feedback also results in single longitudinal mode emission with a SMSR larger than 20 dB, whereas the device operates in multiple longitudinal modes without filtered feedback. The wavelength locking is observed simultaneously in the two counter-propagating directions and remains effective for all currents above threshold. We show that the device's behaviour can be modelled using a two-mode rate-equation model extended with Lang-Kobayashi terms to account for optical feedback. The numerical results from this model are in agreement with the experimental ones. The modeling also shows that, if the feedback is not in-phase with the initial laser field, wavelength locking can be accomplished by increasing the feedback strength.

8431-52, Session 11

High index contrast optical platform using gallium phosphide on sapphire: an alternative to SOI?

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Confinement of light at submicron wavelengths is of great importance for highly specific sensing of bio-molecules and for compact photonic circuits based on waveguiding. Currently this confinement can be achieved through the well established high index contrast silicon on insulator (SOI) platform. However this material combination requires light at wavelengths beyond 1 micron where component cost of the

InP based lasers and photodetectors are very expensive. It is thus of great interest to develop a similar platform that could operate in the range of 850 nm where low cost lasers (e.g., Vertical Cavity Surface Emitting Lasers as used in optical mice) and detectors (e.g., as used in camera phones) are readily available. A possible high index material suited to this application is Gallium Phosphide which has a bandgap of 2.26eV and refractive index of ~ 3.2 at this wavelength. For the highest index contrast, GaP should be grown on a substrate with low index of refraction such as quartz (n=1.5) or sapphire (1.7). We report on the fabrication and characteristics of GaP waveguides grown on c-plane (0001) sapphire substrates using metalorganic vapour phase epitaxy (MOVPE). Growth parameters such as substrate temperature and, in particular, the V:III ratio are reviewed with respect to their effect on the nucleation, surface roughness and uniformity of the films. The structural properties of the films were analysed using Atomic Force Microscopy and X-Ray Diffraction, showing that GaP is growing along the direction and strongly affected by nucleation growth conditions. Optical properties of the GaP layers, as well as those incorporating indium (Ga1-xInxP), were determined by ellipsometry and fibre-coupled waveguide loss measurements. Waveguide ridges were fabricated by etching of the GaP layer using BCl3/Ar plasma etch and optical losses are discussed in terms of the material quality and waveguide processing parameters. A grating coupler of about 40% of coupling efficiency with 35 nm of 1dB bandwidth at the wavelength of 850 nm has also been designed for GaP on sapphire using vectorial finite element method (VFEM) to validate the feasibility of GaP around 850 nm.

8431-53, Session 12

Light propagation in metallic nanoparticle chains on SOI waveguide

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Energy transfer via dipolar interactions between closely spaced metal nanoparticles (MNPs) leads to the formation of highly confined waveguides operated below the diffraction limit. Such localized surface plasmons (LSP) potentially offer a wide variety of plasmonic waveguide configurations since MNPs can be arranged on demand on a substrate. Interfacing LSP waveguide with dielectric waveguide is the next key step for implementation of localized plasmonic functions in photonic circuitry. For this purpose, low-loss silicon waveguides can be cleverly combined with highly confined LSP waveguides provided that MNP chains are sufficiently short to avoid excess losses.

In this work, we demonstrate successful interfacing between LSP and silicon-on-insulator (SOI) waveguides with several outstanding properties. Predictions from theoretical models are fully corroborated by transmission and near-field measurements.

We show that the optical energy carried by a TE SOI waveguide mode at telecom wavelengths can be efficiently transferred into MNP chains deposited on the waveguide top, whatever the number of metallic particles (from 5 to 50). A collective oscillation of MNP dipoles is actually obtained when the frequency and wavevector characteristics (w,k) of the SOI waveguide mode are similar to those of at least one of the MNP chain LSP modes. In the case of the longest MNP chains, the SOI waveguide and the MNP chain can behave as highly coupled waveguides, which induces periodic oscillations of the optical power from one waveguide to the other with record <600nm characteristic lengths.

For any chain length, the SOI waveguide mode phase at the device output is strongly impacted by its interaction with LSP modes. Phase delays of more than pi radians are found in the case of submicronic MNP chains.

In conclusion, we show that short MNP chains represent an attractive building block to implement submicronic and low-loss optical functions in integrated photonic circuits.

8431-54, Session 12

Numerical investigation and characterization of MOS plasmonic waveguides

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Growing needs for increased data traffic drive the development of Si based optical components as these could offer higher bandwidth along with increased energy efficiency. However owing to the diffraction limit, optical components have a much larger cross section than their electronic counterparts, thus inhibiting the possibility of effective integration at nanoscale. One potential way to circumvent this problem of size mismatch is to guide optical signals in the sub-wavelength regime using plasmons. The eventual goal of this work is to investigate a CMOS compatible plasmon waveguide. Among the different proposed plasmonic waveguides, MOS plasmon waveguide [1,2] is of particular interest as these structures could be easily fabricated using the mature Si based CMOS technology. Furthermore, the incorporation of oxide close to the metal interface creates a low loss channel for guiding plasmons. Finally, the metals supporting plasmon modes can additionally serve as electrodes, making those MOS structures ideal candidates for electrical control of optical signals in active devices.

One critical issue yet to be fully understood is the detailed coupling mechanism to the various modes of the MOS stack. We will emphasize here the respective role of both guided and leaky plasmonic modes when light is coupled from an SOI waveguide. For a start, full scale 3D FDTD simulations were carried out for MOS devices of different lengths. Transmission results show FP oscillations corresponding to the fundamental plasmon mode, as well as due to other contributions whose interpretation is ongoing. These plasmonic MOS devices were fabricated on a CMOS foundry. Numerical results will be compared with their experimental characterization.

The device were fabricated on silicon-on-insulator (SOI) platform with a 220nm Si on a 2µm oxide layer using 200 mm CMOS fabrication facility. The device consists of a plasmonic guide in and out coupled to standard SOI photonic guide. A salient feature in the fabricated device is the use of a low optical loss Cu gate metal and thin Si_3N_4 [3] as diffusion barrier.

Transmission measurement as a function of plasmonic guide length was performed using a laser source of wavelength centered at 1550 nm. A methodology for automated and reliable optical transmission, were implemented for wafer level testing. For a MOS waveguide of Si width 250 nm and thickness 170 nm, the estimated propagation length was 0.24 dB/µm, with device insertion loss at 2.8 dB.

[1] J. A. Dionne, K. A. Diest, L. A. Sweatlock H. A. Atwater, Nano Lett. 9, 897 (2009)

[2] A. Hryciw, Y. C. Jun, and M. L. Brongersma: Opt. Express 17 185 (2009)

[3] A. Emboras et al submitted to Opt. Exp.

8431-55, Session 12

Proposal of a silicon optical modulator based on surface plasmon resonance

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A novel silicon optical modulator based on surface plasmon resonance is proposed. This modulator has a metal-oxide-semiconductor (MOS) capacitor structure. The waveguide core is silicon-on-insulator (SOI), and the underlying clad layer is buried oxide. The side and upper clad layers are thin SiO_2 films, and impurity-doped polycrystalline silicon that functions as a gate electrode covers them. An input light propagates inside the SOI core repeating total internal reflections. When applying a bias voltage to the polysilicon gate electrode, the inversion

(or accumulation) layer with high-concentration free carriers is formed. Since the inversion (or accumulation) layer behaves like a metal film, it is expected that the guided waves interact with surface plasmons at the interface of the inversion layer and the gate oxide film at a particular bias voltage. The light coupled with the surface plasmon loses energy because part of light energy moves to the surface plasmon, and a large energy dissipates by a plasma oscillation. As a result, the power of the output light decreases.

If a reflectivity at the interface of waveguide core and clad can be reduced as greatly as possible, the power of propagation light in a waveguide will fall remarkably because propagation light repeats total internal reflection. Therefore, it is possible to fabricate an optical modulator with a small size and high extinction ratio if the surface plasmon resonance can be used. However, since the condition that surface plasmon resonance happens depends on the thickness of the metal thin film, the incident angle of light and so on, it is necessary to estimate various parameters of the optical modulator. In this study, the light propagation properties in a MOS optical modulator based on surface plasmon resonance is analyzed theoretically. The analysis is based on Marcatili's approximation. The gate voltage and wavelength dependences of propagation loss and extinction ratio are evaluated.

8431-56, Session 12

CMOS integration of field effect plasmonic modulator

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Compact and low energy consumption integrated optical modulator is urgently required for encoding information into optical signals. To that respect, the use of plasmon modes to modulate light is of particular interest when compared to the numerous references describing silicon based optical modulators. Indeed, the high field confinement properties of those modes and the increased sensitivity to small refractive index changes of the dielectric close to the metal can help decrease the characteristic length scales of the devices, towards to that of microelectronics.

The scope of this work is to demonstrate an integrated electro-optical plasmonic modulator using standard CMOS technology on LETI platform. The investigated modulators rely on accumulation of carrier in a Cu gate MOS capacitance through which light is transmitted. Fabrication of our modulator require the use of both front-end and Cu back-end technologies, which are properly combined only a few nanometers one from each other thanks to the use of a diffusion barrier layer.

The device is fabricated on silicon-on insulator (SOI) wafers, with silicon channel waveguides serving as the medium of propagating light. The light is coupled to the TM-polarized mode of the photonic waveguides through grating couplers. As the light propagates through the active region (plasMOStor), it couples into a plasmonic mode. The plasMOStor consists of a metal-insulator-Si-metal waveguide where the back metal was fabricated by flipping and molecular bonding of the original SOI wafer on a Si carrier wafer. The active device area varies from 1 to 6 µm2.

Electro-optical (EO) characterization of copper based MOS capacitance is ongoing. Devices show accumulation capacitance of few fF and leakage current below 10fA. A novel coupling scheme was implemented allowing insertion losses as low as 2.5 dB/coupler to be measured. EO measurements show an optical modulation having a capacitive signature, in agreement with simulations.

8431-57, Session 13

Low-nonlinearity and low-loss silicon slot waveguides with ALD-grown thin films

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The slot waveguide facilitates nanoscale light confinement into a low-index material on silicon [1], creating great potential to improve the performance and to increase the functionality of silicon photonic devices. We have shown that thin film growth using the atomic layer deposition (ALD) technique is capable of controlled partial or complete filling of slot waveguides [2,3]. The recent emergence of ALD-grown thin films in the microelectronics industry directly demonstrates the CMOS compatibility of ALD, making the technique attractive for CMOS photonics.

In this work, we present our studies on slot waveguides with ALD coatings. A propagation loss as low as 5 dB/cm is achieved for a deep-UV patterned slot waveguide filled with an ALD grown Al2O3 thin film. The low-index and low-nonlinearity filling material allows nearly two orders of magnitude lower nonlinearities than in silicon waveguides. Therefore, these waveguides are a good candidate for linear photonic devices on the silicon platform, and for distortion-free signal transmission channels between nonlinear devices on a silicon all-optical chip. A double-vertical-slot waveguide with air-slots has been proposed to have a low-nonlinearity [4]. We demonstrate a double-vertical-slot structure using a silicon slot waveguide coated with ALD-grown Al2O3 and TiO2 layers, in which the alumina layer forms the slots. This process technique provides an easy way of fabricating high quality double-vertical-slot waveguides. A propagation loss lower than 10 dB/cm is achieved for this structure.

[1] V. R. Almeida et al., Opt. Lett. 29, 1209 (2004).

[2] T. Alasaarela et al., Opt. Express 19, 11529 (2011).

[3] T. Alasaarela et al., Opt. Eng. 48, 080502-1 (2009).

[4] Y. Yue et al., Opt. Express 18, 22061 (2010).

8431-58, Session 13

Integrated optical waveguide interferometer for geophysical applications

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The Commissariat à l'Energie Atomique et aux Energies Alternatives (CEA) is in charge of seismic and infrasound development about earth monitoring activities. Working principles of geophysical sensors like seismometer or microbarometer are similar. A mechanical part transforms the physical phenomena (ground vibrations or pressure variations) into a differential motion. Then, a transducer converts it into an analog voltage which is digitized. Our need is to increase performances of our sensors by the mean of a wider bandwidth and a higher dynamic. We thought that optical technology can do that. As a consequence, we developed a new transducer using optical technology.

In a first step, we built a Michelson interferometer with bulk optics to validate interest of optical technology in our application and better appreciate parameters of influence. Thanks to this prototype, we demonstrated a motion range higher than 1 cm and a resolution about 1 pm at 1 Hz, which is 20 times lower than electromagnetic transducer and permit to predict a widening bandwidth with optical transducer.

In a second step, we developed and built an integrated optical waveguide interferometer to insert it into our sensors. We present this integrated optical waveguide interferometer and the design chosen that lead to a perfect equilibrium between the reference and the measuring arms. The chip realised is very compact and easy to use. Preliminary results in terms of intrinsic noise, motion range and thermal sensitivity are discussed and the specific signal processing will be explained. Then, first measurements with a geophysical sensor will be presented, and compared with present sensors equipped with electromagnetic transducer.

8431-59, Session 13

Silicon-based monolithically integrated whispering-gallery mode resonators with buried waveguides

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One of the most important requirements on planar Whispering-gallery mode (WGM) resonators is the high refractive index contrast between the cavity and the surrounding media. For this reason, a quasi-freestanding cavity embedded in an air environment is the preferred solution. Most of current cutting-edge experiments with this kind of optically passive and freestanding resonators regularly use tapered fibers to probe the system. This technique, however, faces unstable experimental conditions and limits the meaningful measurement duration to only few minutes. The lack of a freestanding WGM cavity system monolithically interfaced to an input/output coupling waveguide reduces dramatically the chances for immediate applications of these devices.

Here we report on the realization and optical characterization of a CMOS-compatible and silicon-based monolithically integrated platform comprising in a WGM resonator/waveguide coupled system. Wafer-scale integration of freestanding optical devices has been achieved using standard silicon microfabrication technology. The realized devices use a vertical coupling scheme between a microresonator and a rib waveguide. We demonstrate how the overall high optical quality of the system benefits from a perfect glass planarization procedure of the waveguide. The planarization quality is reflected in the measured quality factors of 25,000 at the first telecom window for 50 um diameter devices from very first samples. More importantly, by using a selective isotropic etch we remove the gap material under the WGM resonators obtaining thus freestanding devices (Q~50,000) coupled through an air gap to the bus waveguide. Additionally, our approach allows for a controlled selective excitation of different mode families of the resonator. This technological solutions give important hints for future developments in silicon-based lightwave circuits. In particular, the developed technology opens door for the realization of all-integrated complex resonator systems for sensing, optomechanical and metrological applications, with the potential to substitute the nowadays intensive use of complicated fiber-taper coupling schemes.

8431-60, Session 13

Whispering gallery modes in coated silica microspheres

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Silica microspheres are a very high Q-factor, low mode volume microresonators, meaning that a high light intensity is confined in a small volume for a long period of time. That makes them a very good cavity for lasing applications and for the study of non-linear optical properties of different materials. The light in the microspheres is confined in so called whispering gallery modes, which are localized in the equatorial plane of the microsphere. In this paper we present the result obtained on microspheres coated with a active layer (the active material being erbium). Silica microspheres were made by melting the tip of a standard telecom fiber. The diameter of the microspheres was determined to be around 140 µm. They were coated with a 70% SiO_2 - 30 HfO_2 sol-gel derived glass activated by 0.3 % mol of erbium. The samples were coated using a dip coating apparatus. The thickness of the coating was estimated to be around 1 µm. The deposited films were amorphous, which was ascertained by far-field luminescence measurements. A broad peak corresponding to the 4I13/2 → 4I15/2 Er^{3+} transition at 1530 nm was detected confirming the amorphous nature of the deposited films. The whispering gallery modes of the coated resonator were studied using a full taper - microsphere coupling setup. Upon excitation at 1480 nm sharp peaks were observed in the wavelength range from 1540 to 1565 nm where the erbium emission cross-section is greater than the absorption cross-section. They were attributed to the whispering gallery modes of the microsphere falling in the wavelength range of the erbium emission. The free spectral range of the modes was measured to be 3.7 nm which is in good agreement with the geometrical and optical properties of the spheres (diameter of the sphere was around 140 µm and the refractive index of the coating around 1.6).

8431-14, Session 14

A single-lithography SOI rib waveguide sensing circuit with apodized low back-reflection surface grating fiber coupling

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We present a single-lithography Mach-Zehnder interferometer sensor circuit, with integrated low back-reflection input and output grating couplers. Surface grating couplers have proven efficient for coupling light between single-mode silica fibers and nanometric silicon waveguides. However, the inclusion of grating couplers usually adds lithography steps to photonic circuit fabrication. For rapid prototyping, and cost sensitive applications like disposable sensors, a simple fabrication is a key enabler. Furthermore, in high index contrast systems like SOI, back-reflections into the photonic circuit can produce unacceptable interferences.

Here, the low back-reflection is accomplished by a duty cycle apodization optimized for coupling light between single-mode silica fibers and the nanometric SOI rib-waveguides. We discuss the design, fabrication, and characterization of the circuit. The apodization profile of the gratings is algorithmically generated by eigenmode expansion and the integrated waveguides, splitters, and combiners are designed by finite element simulations. The maximum simulated coupling efficiencies of the gratings are 70% and the MMI splitters and combiners have a footprint of only 19.2 × 4.5 µm2. The devices are fabricated on an SOI wafer with a 220 nm device layer and 2 µm buried oxide, by a single electron beam lithography and plasma etching. We use the negative electron beam resist hydrogen silsesquioxane (HSQ), for short exposure times, and etch the device layer in a $Cl_2/HBr/O_2/Ar$ plasma. We characterize the devices in the wavelength range from 1460-1580 nm and show a pass-band ripple of only 0.06 dB and grating coupling efficiency of 40% at 1530 nm. The integrated Mach-Zehnder interferometer has an extinction ratio of -18 dB at 1530 nm and between -13 and -19 dB over the whole 1460-1580 nm range.

8431-62, Session 14

Low-loss single mode light waveguides in polymer

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We report on the development of a UV-lithography manufacturing process for low loss single mode waveguides in polymer and the characterization of the fabricated components in a broad wavelength range from 634 nm to 1550 nm. The main focus of this work lies in providing a quick and cost efficient production technique for single mode waveguides and low loss integrated optical circuits. To achieve this goal we chose a photo-structurable polymer host-guest-system consisting of SU8 and a low refractive dopant monomer. The polymer

resin was designed to be spin-coatable. The material system enables the adaptation of the optical layer height to a desired wavelength and therefore to specifically design the waveguides to the propagating mode within coupled standard single mode fibers. The manufacturing process was tuned to find parameters to reduce strain and stress within the material and minimize structure loss and polarization dependent loss. Near and far-field measurements at different wavelengths show that the mode propagating within a customized integrated waveguide structure and the mode of a standard fiber exhibit a mode overlap value of approximately 1 and suffer only very low aperture loss at the coupling interfaces. As a result, we were able to measure an average insertion loss of 1.3 dB and a polarization dependent loss of approximately 0.2 dB on sets of test structures of 36 mm length at a wavelength of 1310 nm. Thus, with calculated coupling losses of 0.3 dB due to aperture and mode field loss, we measure an intrinsic attenuation of 0.3 dB/cm. We measured approximately 0.2 dB/cm material attenuation at 1310 nm wavelength for the used SU8 material before cross-linking. The presented production technique is suitable to provide low loss and low cost integrated optical circuits for sensor and communication applications in different wavelength ranges.

8431-63, Session 14

Slot ring biosensors using silicon nitride waveguides with small temperature coefficient

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Early detection and early treatment of diseases are very important especially for the aging society. Presenly Enzyme-Linked ImmunoSorbent Assay (ELISA) is widely used for the detection of antigen-antibody reaction. We are developing the antigen-antibody reaction sensor by using the advanced Si semiconductor technologies (Fukuyama et al. Jpn. J. Appl. Phys 50, 2011, 04DL11). The Prostate specific antigen was detected by using Si ring resonator at the concentration of 1e-5 g/ml. However, the sensitivity should be increased by two orders of magnitude more for the practical use. Also the temperature dependence of the Si refractive index is very large.

In this paper we employed the silicon nitride (SiN) waveguide to decrease the temperature dependence and slot waveguide (Claes et al. IEEE Photonics J.1 (2009) 197) to increase the sensitivity. The sensitivity increase mechanism is as follows: The light intensity at the slot is maximum and the biomaterial is adsorbed on the sidewall of the slot. Therefore, the sensitivity is dramatically enhanced compared with the normal waveguide. From our simulation the sensitivity is about one order higher for the slot width of 100 nm and the waveguide width of 500 nm and wavelength of 1300 nm.

We investigated the temperature dependence of the SiN slot waveguide and it is shown that the resonance wavelength shift of the SiN ring resonator (slot width 100 nm, ring circumference length 10 micro meter) is 1/8 of the Si ring resonator. Next the sensitivity was evaluated using the sucrose solution. The result showed that the sensitivity is about one order of magnitude higher than that of Si ring resonator. In this case the quality factor of the SiN ring resonator is only 2000 and that of the Si ring resonator was 5000. Therefore, by improving the quality factor of the SiN ring resonator the sensitivity will further increased. Biotin-Streptavidin detection is succeed at the concentration of 100 ng/ml. Now we are trying to improve the sensitivity.

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8432-01, Session 1

High-speed VCSELs for energy efficient computer interconnects

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We review state-of-the-art vertical-cavity surface-emitting laser (VCSEL) based optical interconnects for high performance computing and promote the ~980 nm-range VCSEL as a key component to realize energy-efficient short and very short-distance optical interconnect systems. Traditional electrical interconnects experience significant efficiency limitations at bit rates exceeding ~10 Gb/s including signal attenuation, crosstalk and high power consumption. Optical interconnects based on VCSELs have replaced intra-rack electrical interconnects and are expected to soon dominate shorter link distances including board-to-board, module-to-module, and chip-to-chip optical interconnects.

For short-distance interconnects the wavelength of 980 nm has important advantages. At first GaAs is transparent at this wavelength. Thus densely-packed, flip-chipped bottom-emitting VCSELs for silicon photonics can be realized. Furthermore, highly strained InGaAs active regions provide deeper electron and hole confinement potentials and, simultaneously, a large differential gain can be realized. Both factors are essential for pushing the limits towards ultra-high speed. In addition binary DBR mirrors can be used and thus a higher thermal conductance can be achieved for effective heat extraction as compared to the 850 nm devices. Therefore, highly temperature-stable high-speed performance can be realized.

The 850-nm spectral range is the current standard for optical interconnects based on multimode fiber. We demonstrate record energy-efficient data transmission with our 850 nm single-mode and quasi-single mode VCSELs for multimode optical fiber link lengths up to 1 km at bit rates up to 25 Gb/s.

Record speed error-free data transmission is presently achieved for our 980-nm devices resulting in 44 Gb/s operation at room temperature and in 50 Gb/s for Peltier-cooled devices. Temperature-stable 40 Gb/s operation is realized at constant driving parameters across a large temperature range up to 75 °C. We demonstrate energy-efficient 35 Gb/s operation with a low dissipated heat-to-bit rate ratio of 233 mW/Tbps. Thus 980-nm VCSELs are excellent candidates for short-distance optical interconnects.

8432-02, Session 1

New standards in high-speed and tunable long wavelength VCSELs

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Invited Talk: Since the invention of the first vertically emitting laser device in 1988 by K. Iga lots of technologically related constraints have been solved and overcome. In combination with proper electrical, optical and thermal designs the Vertical-Cavity Surface-Emitting Lasers (VCSELs) of today are offering new perspectives with respect to security issues, sensing applications and data transmission. In order to cope with the requirements for optical networks, interconnects or Ultra-High-Definition-TV modifications proved to be necessary concerning the previous long-cavity InP buried tunnel junction (BTJ) VCSEL designs emitting in the 1.3µm and 1.55µm ranges. The new short-cavity (SC) VCSEL design with highly compressively strained quantum wells, low doping sequences at overgrowth, adjusted layer thicknesses and mirror diameters offer direct access to the design of photon life times, differential gain, thermal resistance, dimensions of active volume and parasitic losses in the device. Consequently the desired increase of modulation bandwidth up to 18 GHz with 3.7 mW optical output power for a 4.5 µm BTJ diameter has been successfully achieved. Slight modifications of the active region (i.e. mode-gain offset), of the mesa diameter and cavity length transferred its high-speed property at the same time to a high-power one. As a result, a 5.5 µm BTJ SC-VCSEL has been developed with 6.7 mW optical output power at room temperature (and 3 mW at 80°C), a side-mode suppression ratio beyond 50 dB over the whole temperature range, a wallplug efficiency of 25% and a modulation bandwidth exceeding 11 GHz. The electro-thermal tuning covers spectral ranges of the order 5 to 7 nm. The high-power laser even tunes over 12 nm under special conditions.

8432-03, Session 1

Hybrid integration approach of VCSELs for miniaturized optical deflection of microparticles

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Over the last decades, increasing effort was spent for the miniaturized handling of micrometer-sized particles in microfluidic channels without any mechanical contact. Optical traps offer this unique possibility. However, typically used trapping laser setups are rather bulky and expensive. VCSEL (vertical-cavity surface-emitting laser) arrays in contrast enable miniaturization by means of integration as well as the parallel manipulation in an optical lattice.

Commercially available VCSEL arrays typically have a pitch of 250 µm. Interruption-free manipulation without additional optics requires densely packed arrays with a pitch reduced by an order of magnitude. The fabrication of these arrays is much more challenging. In recent years we have shown purely optical deflection of micrometer-sized polystyrene particles inside microfluidic channels by means of ultra-densely packed arrays of AlGaAs-GaAs-based VCSELs. These laser diode arrays are supposed to enable particle redirection into either branch of a microfluidic Y-junction. However, an earlier integration concept to achieve high miniaturization failed due to insufficient heat dissipation and therefore limited output power.

Our new approach provides a different realization scheme for the ultra-miniaturized integration concept. A crucial part is the combination of the laser chip and a structured heat sink.

We present the design, fabrication, and properties of AlGaAs-GaAs-based vertical-cavity surface-emitting laser arrays. Furthermore, we show the integration of the described lasers with microfluidic chips. The microfluidic component consists of Y-shaped channels with widths of several tens of micrometers. One possibility to achieve the challenging integration is the fabrication of top-emitting VCSELs with tailored bonding grooves to minimize the gap between lasers and microfluidic chip. Another possibility for the integration is shifting to bottom-emitting lasers, flip-chip soldered with subsequent substrate removal. Finally, after the merging of laser chip and heat sink, the lasers are characterized with respect to their thermal behavior.

8432-04, Session 1

Transverse mode and polarization characteristics of AlGaInP-based VCSELs with integrated multiple oxide apertures

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Red-emitting vertical-cavity surface-emitting lasers (VCSELs) are attractive candidates, due to their electrical and optical characteristics. In short-haul optical data transmission via polymer optical fibers (POF), for example, AlGaInP-based VCSELs meet one attenuation minimum at around 650 nm. The outstanding laser characteristics, low threshold current of 1 mA, output power up to 3 mW and especially the transverse mode profile are mainly determined by the size of the monolithically integrated oxide aperture. For different applications the fundamental mode is desirable as well as a stable linear polarization, because polarization instabilities limit the error free data transmission. One additional restricting parameter for high speed data transfer is the intrinsic low pass of the laser device. Here, parasitic capacitance can be reduced, for example, with additional multiple oxide apertures.

In the current work, we show detailed analysis of the transverse beam profile and polarization characteristics of devices with one and three oxide apertures. A Gaussian transverse beam profile is achieved with an oxide aperture of less than 6 µm. The laser light is linearly polarized with a high degree of polarization (> 97%) during the complete current range. The stable polarization direction [011] can be attributed to ordering effects during MOVPE growth of the GaInP material system and a reduction in crystal symmetry.

Different oxide aperture diameters can be implemented in one device due to high oxidation selectivity of the Al(x)Ga(1-x)As layer depending on aluminum content. These deep oxidation layers lead to a reduction of the parasitic capacitance, while beam profile and polarization characteristics are not affected.

8432-05, Session 1

VCSELs with two-sided beam emission for pressure sensor applications

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A novel type of all-optical pressure sensor has been developed. The compact-sized device interferometrically measures relative changes of refractive index of air by means of a rigid, air-spaced Fabry-Pérot etalon. This design is so sensitive that the transducer is applicable as a microphone. A relative change of refractive index of ∆n = 10e–14 has been measured in a demonstrator laboratory setup. However, it was found that the noise floor of the sensor is governed by the intrinsic noise of the laser source used for interrogation. A common approach to overcome this limitation consists in employing a balanced detection scheme, where the measuring signal is subtracted from a reference signal. The latter is usually generated by a beam splitter or a beam sampler. However, the additional optical axis contradicts the desired compactness and cost efficiency of the sensor. Therefore, a suitable VCSEL has been designed to provide simultaneous light emission from both facets. One beam serves as measuring signal while the other establishes a reference; and both paths lie on the same optical axis.

VCSELs for two-sided emission have been processed from molecular beam epitaxially-grown wafer material based on active InGaAs quantum wells for laser operation close to 960 nm wavelength where the GaAs substrate is transparent. The reflectivities of the Bragg mirrors were adjusted to yield power outcoupling ratios in the range of 1-to-2 to 1-to-3. Among others, the processing involved selective oxidation of current apertures for transverse single-mode oscillation, annular contact formation, substrate thinning, and the deposition of a rear side anti-reflection coating. The lasers were mounted on printed-circuit boards with optical through-holes for convenient handling in the measurement setup.

The noise behavior of such modified VCSELs is investigated. With regard to the sensor application in acoustics, the focus of the study is put on the low frequency, i.e. kHz, regime. While laser diode noise performance is readily available for the MHz to GHz frequency range, only very limited data exists in the Hz to kHz domain. The relative intensity noise of both beams is measured and compared and the mutual coherence properties are investigated. In order to minimize the influence of the supply current on the noise performance of the laser, a low-noise driver has been specially designed, exhibiting a self-noise of 100pA/sqrtHz. Additionally, frequency noise (FM noise) is analyzed by converting wavelength jitter into an intensity signal (AM noise) by the use of a frequency discriminator, a solid Fabry-Pérot etalon of finesse 30.

Laser RIN is measured to be around -110dB/Hz at 1 KHz showing strong 1/f behavior despite the improved driver design. It is found that FM noise converted to AM noise dominates over RIN by about 30dB within the specific setup. However, excellent correlation properties are found between the two beams. Therefore, shot noise level (-150dB/Hz at 1 kHz for 550µW) was reached in a balanced setup. The implementation of the developed VCSEL into the described pressure sensor is expected to result in a highly compact and high-performance microsystem.

8432-06, Session 2

New confinement method for monolithic GaSb-VCSEL emitting in the mid-IR

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The atmosphere transparency window between 2 and 2.5 µm is of particular interest due to the presence of absorption lines of many pollutants, such as CH4, CO2, CO, which can be easily detected by Tunable Diode Laser Absorption Spectroscopy (TDLAS) [1]. Vertical cavity surface emitting lasers (VCSEL) exhibit characteristics such as single mode operation and wide mode hope free tuning particularly well adapted to TDLAS. Recently, hybrid VCSELs grown on GaSb substrates and operating at room temperature up to 2.6µm have been reported with best results achieved with buried tunnel junctions (BTJ) [2]. This technology however requires a regrowth step which is very touchy and makes it complicated and time consuming. A second approach based on an etched-pillar monolithic VCSEL using 2 N-type DBR mirrors with a TJ demonstrated CW operation up to 20°C [3]. These devices however lacked appropriate current and optical confinements for practical use.

In this communication we report on the improvement of the monolithic structure in which we selectively etch the TJ in order to constrict the current pathway. This technique is allowed by the high wet-etching selectivity existing between InAs forming the TJ and the Sb-based material around the TJ [4]. With this new process we have obtained CW operation up to 75°C, with threshold current as low as 12mA for a 16 µm effective diameter. The emitted wavelength is around 2.3 µm at 300K. These results open the way to the realization of monolithic Sb-based VCSEL suitable for TDLAS.

[1] Vicet A; Yarekha D.A; Perona A; Rouillard Y; Gaillard S; Baranov A.N - Spectrochim. Acta - Part A 58 2405 (2002).

[2] Bachmann A; Arafin S; Kashani-Shirazi K - New J. Phys - Vol.11 125014 (2009).

[3] Ducanchez A; Cerutti L; Grech P; Genty F - Photonics Technology Letters - Vol. 20, no. 20, p.1745 (2008).

[4] Dier O; Lin C; Grau M; Amann MC - Semicon. Science and Tech. - Vol.19, no. 11, p.1250 (2004)

8432-07, Session 2

Single-mode InGaAs/GaAs 1.3-µm VCSELs based on mode-profile engineering

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Single-mode 1.3-μm vertical-cavity surface-emitting lasers (VCSELs) are potential low-cost, power-efficient sources for metropolitan and access networks. However, the realization of singlemode VCSELs with sufficiently high power is inherently difficult since a large device diameter, as required high power emission, tends to support transversal multimode operation. To circumvent this problem, several approaches have been investigated by different groups1. In our previous work, a novel scheme of mode-profile modulation using intra-cavity patterning for improved mode-gain overlap to achieve high-power single-mode operation was proposed and demonstrated2.The advantages of this scheme are relatively simple processing procedures and high singlemode to multimode power conversion efficiency, e.g. compared to approaches using selective mode-loss mechanisms. The device is based on highly strained InGaAs/GaAs quantum well with large gain-cavity tuning to push the emission wavelength into the 1.3-μm band and uses regrown current blocking layer for current confinement. The output power reported in that study was relatively modest because of the mismatch between the nodes of the electromagnetic field and the modulation-doping current-spreading layers in the cavity.

In this paper, we report on the optimization of such VCSELs. The device structure has a better tuning to better control the losses and an AlGaAs instead of GaAs n-doped blocking layer is used to provide better confinement, both electrical and optical. The near-field mode distribution is measured to investigate the effect of mode-modulation and the potential of such device for high-speed applications is analyzed.

8432-08, Session 2

Three-dimensional simulation of 1300-nm AlGaInAs VCSEL arrays

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The efficient way to increase the emitted power by VCSEL is to combine several emitters into phase-locked array. Vertical geometry of device assures narrow linewidth by selection of single longitudinal standing wave being in the resonance with quantum wells. Sole mechanism contributing to the linewidth broadening originates in the existence of lateral modes of two kinds. First kind are modes of single emitters, second are the array supermodes formed of the same order of single-emitter modes. The key to narrow spectral linewidth is control of the number of existing modes. First kind can be governed by the dimension of the single emitter or patterning of optical confinement, the control of the second kind of the modes is far more problematic.

We present the optimization of the carrier injection, heat flow and optical confinement aimed for single mode operation. The analyzed structure incorporates InAlGaAs quantum wells within InP cavity. The cavity is bounded by AlGaAs/GaAs DBRs The tunnel junction is responsible for carrier funneling into the active region. The air-gap etched at the interface between cavity and top DBR provides the confinement of the lateral modes. To rigorously simulate the physical phenomena taking place in the device we used multi-physical model, which comprises three-dimensional models of optical (Plane Wave Admittance Method), thermal and electrical (Finite Element Method) phenomena.

We perform the exhaustive modal analysis of the 1x3, 1x4 and 2x4 VCSEL arrays. In the analysis we investigate the influence of the distance between emitters, their size and etching depth. The analysis is performed for broad range of injected currents from threshold to the rollover. As the result we illustrate the complex competition of the modes, influence of the optical confinement on structure of the modes and determine the geometrical parameters, which favor the array modes in the considered array designs.

8432-09, Session 2

Polarization mode structure in long-wavelength wafer-fused vertical-cavity surface-emitting lasers

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Applications of long-wavelength ($\lambda > 1$ μm) vertical-cavity surface-emitting lasers (VCSELs) generally require close control over wavelength and polarization of the emitted light. In most cases, single mode lasing is desired. The suppression ratio of the side modes, i.e. higher-order transverse modes (HOTMs) and polarization modes (PMs) compared to the fundamental mode (FM) should generally be large enough, typically more than 30 dB.

We report on the detailed modal analysis of wafer-fused 1550-nm wavelength VCSELs incorporating an InAlGaAs/InP active region, a re-grown circular tunnel junction (TJ) and undoped AlGaAs/GaAs distributed Bragg reflectors. We experimentally determined the diameter of the TJ that optimizes the output power, threshold current and SMSR, finding a value of 6 μm. Moreover, we investigated the impact of the TJ aperture diameter on the mode structure. A large batch of devices was investigated, allowing drawing conclusions on typical behavior of these devices.

The measured emission spectra show that the fundamental spatial mode is split into two orthogonal PMs, which are spectrally separated by δ, referred to here as the birefringence parameter. We observed that this parameter is independent of current but depends on the particular chip, suggesting that it is caused by stress, growth inhomogeneities, or etched mesa shape. We also found that the HOTMs show similar polarization doublets with a splitting also equal to δ. This suggests that the birefringence results from effects not particular to the mechanism of mode confinement. Finally, we experimentally studied the dependence on the injection current of the spectral separation Δ between the fundamental mode and the first-order transverse mode. We observed that Δ increases linearly with the current, with a slope depending only on the TJ aperture diameter. This confirms that the mode confinement is induced by the structured TJ, and possibly also to a temperature distribution induced by the current injection.

In conclusion, the mode structure of the investigated batch can be described by two empirical parameters: the spectral shifts Δ and the birefringence δ. The observed behavior of these parameters will enable a further calibration of VCSEL numerical models.

8432-10, Session 2

Electro-optically modulated coupled-cavity VCSELs: electrical design optimization for high-speed operation

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Vertical-Cavity Surface-Emitting Lasers, due to their properties, are one of the best choices for optical communication purposes. Direct modulated VCSELs have reached error free operation at speed of 40 Gbit/s [1] however, the cut-off frequency is limited by relaxation oscillation phenomenon. Recently, it has been suggested that properly designed Coupled Cavity VCSEL with one cavity used as a reverse-biased Electro-Optic Modulator, can be only limited by the 3 dB electrical bandwidth cut-off frequency [2-4]. Therefore, it is important to develop a high-speed electrical design for such VCSELs.

In this paper we first present an analysis of an electrical equivalent circuit of EOM CC-VCSEL with lumped electrodes. We base our design on typical high-speed structures reported in the literature. We optimise our structure with respect to modulator cavity length, number of top and middle distributed Bragg reflectors, doping levels of layers, radii of both mesas and non-ion implantation region in the DBR as well as the contact pad area. We show that the most influencing parameters are the mesa capacitance, series resistance and polyimide capacitance. The 3 dB bandwidth is enhanced by reducing the contact pad area and modulator cavity diameter, together with increasing the modulator cavity length. Faster operation is provided by pnp structure, instead of of npn - one. A realistic structure design that is theoretically able to work with a 100 GHz modulation speed is suggested.

Finally we also discuss the possibility of using a design concept of a EOM CC-VCSEL based on travelling wave electrode configuration.

[1] P. Westbergh, et al., Electron. Lett., 46, pp. 1014-1015, 2010.

[2] A. Paraskevopoulos, et al., in OFC Conference, 2006, p. PDP22,

[3] V. Shchukin, et al., in Proc. of SPIE, vol. 6889, 2008, p. 68890H.

[4] M. Yakimov, et al., J. Vac. Sci. Technol. B, 28, C3G32, 2010

8432-11, Session 3

Long wavelength VCSELs and VECSELs fabricated by wafer fusion: technology and applications

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Among different approaches of long-wavelength vertical cavity emitting device fabrication, wafer fusion represents now a well-established technique for producing state of the art performance in the 1310 nm and 1550 nm wavelength bands. Recent advancements of this technology demonstrate a new, low power consumption alternative to existing 40 and 100 Gbps Ethernet solutions based on edge-emitting lasers. Wafer-fused vertical cavity surface emitting lasers (VCSELs) operating in the 1310 nm band have reached both performance and reliability requirements for entering a large-scale application in 4x10 Gbps coarse wavelength division-multiplexing (CWDM) transmission in four channels at 1271, 1291, 1311 and 1331 nm. At the same time, 1550 nm band VCSELs are very well placed for entering the 10x10 Gbps transmission scheme that is currently considered in the industry as a low cost alternative to the standardized 4x25 Gbps in the 1310 nm band.

The wafer fusion approach proved also to be very successful in demonstrating state of the art optically pumped vertical external cavity surface emitting lasers (VECSELs). Thanks to the excellent thermal properties of InAlGaAs/InP-AlGaAs/GaAs wafer fused gain mirrors, these devices are capable of producing multi-Watt level diffraction limited beams in the spectral range of 1200 nm up to 2000 nm. This wavelength agility represents an important advantage compared with existing solid-state and fiber lasers. One example of a possible large-scale application of wafer-fused VECSELs is for optically pumping Raman fiber lasers and amplifiers.

Even though optical pumping of high power VECSELs is well accepted in the industry, electrically pumped devices are expected to offer a considerable cost and size reduction. One important challenge in the quest for high performance electrically pumped VECSELs consists in reaching uniform pumping of large apertures that are several orders of magnitude larger than in VCSELs. This objective becomes even more challenging in long wavelength VECSELs that are based on un-doped DBRs. By introducing several design modifications in our standard VCSELs fabrication approach that is based tunnel junction injection, we have demonstrated a first wafer-fused electrically pumped VECSEL emitting at 1500 nm. Although these first devices emit in continuous wave in the mW-level, further improvements are expected to produce 100 mW- and even W-level performance.

8432-12, Session 3

Room temperature continuous-wave lasing in microcylinder and microring quantum-dot laser diodes

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We demonstrate RT CW microlasers, based on a high-quality AlGaAs µ-cylinder and µ-ring resonator [1].

We fabricated two families of devices, embedding respectively InGaAlAs and InGaAs quantum dot-in-a-well (DWELL) that were optimized for operation at elevated temperatures. The active layer is inserted in a 256 nm-thick AlGaAs layer, whose Al content increases from 18 % to 30 % as the distance to the active layer increases. To ensure vertical photonic confinement, this central layer is sandwiched

by Al0.3 Ga0.7 As claddings. The lateral confinement is obtained by reactive ion etching on a pre-defined pattern. The top (bottom) contacts are made of Ti-Pt-Au (Ge-Au-Ni-Au).

The samples are excited using two sharp metallic tips and the light is collected with a multimode optical fiber of 0.2 N.A, making a small angle (10°) with the equatorial plane of the sample, so as to maximize collection. The first (second) device family exhibits WGM lasing around 910 nm (1270 nm), with quality factors exceeding 60 000 around threshold.

In a second step, we define ring resonators with decreasing wall thicknesses. Lasing still occur up to 50°C, which demonstrates that the heat sinking properties are not altered in those structures, and we observe a significant drop of the lasing threshold as the central part of the µ-cylinder is removed.

Furthermore, we observe that WGMs with a high radial order are suppressed, thus simplifying the lasing spectra. In this conditions, single-mode and two-color lasing can be obtained simply by adjusting the injected current, opening the way for future applications [2].

[1] Munsch et al. submitted to APL (2011)

[2] Andronico et al. Opt. Lett. 33, 2416 (2008)

8432-13, Session 3

Absorption spectra of a quantum dot laser device with integrated electro-optic modulator

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Self-organized quantum dot (QD) laser structures with integrated electro-optic modulators (EOM) are attractive for applications in optical communication systems because electro-optic eects like the quantum conned Stark eect (QCSE) are particularly strong in QDs.

In this work we study the inuence of modulator voltage, optical input and band structure on the absorption spectrum of a QD EOM and investigate the dynamics of a laser device with integrated EOM.

Our theoretical model is based upon semiconductor Bloch equations which describe the coupled polarization and population dynamics and a traveling wave eld equation.

The impact of the QCSE, a red shift of the wavelength of the optical transition and a decrease of the oscillator strength through the shift of the energy levels and the distortion of the wave functions when a voltage is applied to the modulator, is included in the model. The interaction between the QD levels and quantum well is taken into account by voltage-dependent tunneling and thermal-escape rates, the interplay between the QD ground and excited state are described by constant escape and capture rates.

Since the tunneling rates depend strongly on the energy spacing between the quantum well and the QD levels as well as on the eective mass, it is essential to survey the dynamics of electron and hole occupation probabilities in the QD separately.

Our simulations show that it is crucial both to include the QD excited state and to distinguish between electrons and holes to describe the absorption recovery properly.

The absorption recovery time can be optimized by tuning the energy spacing. That makes a laser device with integrated EOM an excellent candidate for switching applications in an optical communication system. The simulated absorption spectra are in

good agreement with experimental results.

8432-14, Session 3

Quantum dot microlasers with external feedback: a chaotic system close to the quantum limit

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Advances in semiconductor nanotechnology have triggered considerable research and development of photonic devices on the nanoscale such as single photon sources and quantum dot - microcavity lasers. Such microscale light sources feature specific emission characteristic which are related to the quantum nature of the involved emitters. For instance, experimental and theoretical studies of these microlasers reveal a highly sensitive dependence of the photon statistics on the device features and operating conditions.

In this work we address the unexplored field of lasing in microcavites with self-feedback close to the quantum limit. A finite fraction of the emission of an electrically driven quantum dot micropillar laser is reflected back into the microcavity by an external mirror. This self-feedback results in a dramatic change in the photon statistics above threshold where the second order photon autocorrelation function at times zero, g(2)( ), exhibits super-thermal values up to 3.51±0.06. This unique type of strong photon bunching is observed close to and far above the laser threshold and fundamentally differs from g(2)(0)=2 and g(2)(0)=1 expected for thermal light and coherent laser light, respectively. Super-thermal bunching occurs simultaneously with a revival of the bunching signal with a round trip time of the external cavity and a decrease in the coherence time. As such it is indicative of random intensity fluctuations associated with the spiked emission of light at the nW level.

Our results give first insight into the chaotic behavior of microlasers with self-feedback and could pave the way for nanoscale physical random number generators and elements in advanced secure communication networks with synchronized chaotic intensities.

8432-15, Session 3

Intra-cavity absorber photocurrent characteristics of a quantum dot laser emitting on two emission-states: experiment and simulation

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vQuantum dot (QD) absorbers are an essential part in the layout of multi-section semiconductor QD lasers for the generation of pico- or femto-second short optical pulses (Rafailov, E.U. et al., Nature Phot. 1, 395 (2007)). Recently, a resistor Self-electro-optic-effect device (R-SEED) configuration has been applied to the absorber section of a strongly-chirped two-section QD laser where ground state (GS) and excited state (ES) emission of a two-section quantum dot laser could be controlled (Breuer, S. et al., Electronics Lett. 46(2), 161 (2010)). At zero Volt reverse bias, a transition from ES to GS lasing with increasing gain current has been demonstrated (Breuer, S. et al., Appl. Phys. Lett. 97, 071118 (2010)). Subsequently, the influence of an increased reverse bias applied to the absorber, was studied in detail both experimentally and by simulations (Breuer, S. et al., IEEE JQE 47(10), 1320 (2011)). In addition, here, we exploit the QD absorber as an intra-cavity photodiode both experimentally and by simulations. By variably biasing the absorber either with a reverse bias or with a variable external resistor (R-SEED), the escape of the photo-generated carriers in the QD states in the absorber can be controlled. In the R-SEED regime where the absorber is operated in “photoconductive” mode, a steep increase in photo current is observed with decreasing the external load resistance, when the ES joins the GS emission. GS emission and a low photocurrent in the R-SEED regime is achieved thanks to the highly reduced carrier sweep out in the absorber due to the positive photo-generated junction voltage, induced by the load resistance, that causes a strong bleaching of the GS absorption. In reverse bias operation, we find a shallow increase in photo current with increasing reverse bias. By joining both resulting photocurrent regimes, we are able to discuss the respective contributions of carrier capture and escape in the absorber on the photocurrent. The obtained experimental results are in excellent qualitative agreement with time-domain travelling-wave equation modelling.

8432-16, Session 4

High-performance GaAs/AlGaAs quantum cascade lasers: optimization of electrical and thermal properties

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The quantum cascade laser (QCLs) is unipolar device based on tunneling and intersubband transitions, in which the electronic states, wavefunctions and lifetimes of relevant states are engineered through the quantum mechanical confinement imposed by a complex multilayer structure. The principle of operation of QCL structures places stringent requirements on the individual layer thickness and composition as well as the overall periodicity of the whole structure. Another crucial problem of QCLs' operation are the heating effects, which are distinctly larger than in the state-of-the-art bipolar lasers.

In this paper we present the development of mid-infrared GaAs/AlGaAs QCLs technology and discuss basic characteristics of lasers fabricated at the Centre of Nanophotonics at the Institute of Electron Technology [1,2]. We also show that reliable simulation methods which can deal with the complicated physical phenomena involved in the quantum cascade lasers operation are necessary to predict the behaviour of new

structures and optimize their performance [3]. The developed lasers show the record pulse powers of 6 W at 77 K and up to 50 mW at 300 K. The devices have been successfully used in prototype ammonia detection system working in ppb range.

[1] K. Kosiel, M. Bugajski, A. Szerling, Photonics Letters of Poland, 1, 16 (2009)

[2] K. Kosiel, M. Bugajski, A. Szerling, Terahertz and Mid Infrared Radiation, NATO Science for Peace and Security Series B, Physics and Biophysics, Chapter 13, Springer(2011)

[3] G.Hałda , A. Kolek, I. Tralle, IEEE Journal of Quantum Electronics, QE-47, 878, 2011

8432-17, Session 4

Quantum cascade lasers with optimized facet reflectivity

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Quantum cascade lasers (QCLs) based on intersubband transitions are mid-to-far infrared light sources serving a wide range of applications, such as gas sensing, detection of hazardous substances and free space optical communication. Compared to near-infrared semiconductor diode lasers, however, QCLs still suffer from limited wall plug efficiency, thus converting most of the injected electrical power into heat rather than into light. As QCLs are typically operated at current densities twice to three times the threshold current densities, an efficient way to improve power efficiency is to reduce threshold current. Apart from active region design and epitaxial layer quality, also proper management of resonator losses can be an effective means of reducing threshold current. Adjusting the output facet reflectivity is a common way to optimize the power efficiency for a given laser structure and required output power level. Here, we present a study of the optimum facet reflectivity as a function of various electrical and optical characteristics of QCLs emitting around 4.7 µm. In addition, varying the output facet reflectivity and measuring the wall plug efficiency allows for a verification of the theoretical predictions.

8432-18, Session 4

Effect of cavity length on the lasing spectra and far-field intensity distribution of mid-infrared quantum cascade lasers

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The far-field intensity distribution of a quantum cascade laser (QCL) is an important parameter which determines how much of the laser output power can be collected using a given lens system, and thus coupled into a subsequent optical system. Furthermore, changing of the operation parameters such as driving current and temperature can result in strong far-field instabilities.

In the present study we analyze far-field intensity distributions and lasing spectra of 7.7 µm-emitting double-trench QCLs with a typical ridge-width of 13 µm and different cavity lengths, operated in short-pulse mode. For short cavity lengths of around 1 mm, asymmetric multiple-lobe far-field patterns are observed. Increasing the cavity length to 2-4 mm results in a narrower and more symmetric far-field intensity distribution. The lasing spectra are composed of several mode packets and increase in overall width with increasing cavity length.

The observed far-field intensity distributions arise from multiple longitudinal and transverse mode operation with both incoherent and coherent coupling between different occurring modes. Strong pulse-to-pulse variations clearly show multiple possibilities for modes to couple as revealed by near-field intensity measurements for a given laser with fixed operation parameters. Angle-resolved emission spectra allow to assign certain spectral features to specific far-field patterns. They provide clear evidence for coherent coupling between certain modes, resulting in the observed asymmetric far-field patterns. Experimental far-field patterns are compared to model calculations, providing detailed insight into mode coupling mechanisms and phase distributions as a function of cavity length.

8432-19, Session 4

Facet reflectivity reduction of quantum cascade lasers by tilted facets

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Quantum cascade lasers (QCLs) are high power light sources in the mid-infrared (MIR) and terahertz (THz) regimes, with advantages such as freely designable emission wavelength, continuous wave and high temperature operation. The resonator mirror of the QCL, generally, is accomplished by a cleaved facet for optical feedback and its reflectivity is around 30%. Reduction of the Fabry-Pérot resonances by controlling the reflectivity is useful for a lot of applications, such as distributed feedback (DFB) lasers, superluminescent light emitting diodes, optical laser amplifiers, and external cavity light sources. In order to enhance the spectral performance of such applications, the Fabry-Pérot resonances in the laser should be minimized as much as possible. This can be accomplished with surface antireflection (AR) coatings, but AR coatings are thicker for the MIR region and the adhesion between a facet and coatings can be fragile, due to materials selection and the built-in stress. The used QCL heterostructure was grown on a low-doped n-type InP substrate by molecular beam epitaxy (MBE). It consists of 35 cascades of a InGaAs/InAlAs two-phonon resonance active region, embedded between two 0.5 µm thick n-type InGaAs layers. The emission wavelength of the QCLs is ~8 µm at 293K.

In this work, we report on the dependence of facet reflectivity reduction as a function of the angle of the QCL facets. The polarization of the light of QCL is determined by the intersubband selection rules, namely the electric field of the optical wave is directed along the growth direction, creating TM polarized light. This polarization purity enables utilizing the known Brewster's angle to minimize the Fabry-Pérot resonance. As a result of the reduced reflectivity, the highest Jth in this experiment is observed for the 17° facet angle, which is in agreement with the calculated Brewster's angle. Additionally, the direction of the emitted laser light is the refraction to the facet angle as predicted by Snell's law. The far field shows that the vertical mode profile is a single-lobe distribution for the 17° of facet angle.

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8432-20, Session 4

Experimental analysis of thermal properties of AlGaAs/GaAs quantum cascade lasers

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The quantum cascade lasers (QCLs) are the most advanced class of semiconductor sources operating in the mid-infrared wavelengths (3.5 -24 µm) and also in the terahertz range (1.2- 4.9 Thz). The large electrical power density required for operation, and the low thermal conductivity of complex multilayer heterostructure contribute to high temperature gradients in the device. Elevated temperature causes the leakage of electrons from the upper laser level into delocalized continuum states and backfilling of the lower laser level; both effects decreasing the population inversion. These are the main limiting factors of the high temperature operation of the devices. For the purpose of this work, several experimental techniques will be used for the characterization of

QCLs: thermoreflectance spectroscopy, Raman spectroscopy and micro-photoluminescence.

We report, the detailed investigation of thermal performance of quantum cascade lasers, with a particular emphasis on the influence of different mounting options and device geometries, which are compared in terms of their influence on the relative increase of the active region temperature. The device thermal resistance, as well as electronic and lattice temperatures are derived from the experimental data. The experimental results show that mounting (epi-up or epi-down) has little influence on the device performance in short pulse regime. The thermal resistances of 15 µm devices are the highest among the investigated device widths. By combining the experimental and numerical results, an insight into the thermal management in QCLs is gained. The thermal optimization of the design focuses on optimization of heat dissipation in the device, improving the thermal behavior of QCLs. This is essential in order to increase the maximal operation temperature to further progress the applications of the QCLs.

8432-21, Session 5

Room temperature continuous wave interband cascade lasers for gas sensing

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The wavelength range from 3 µm to 4 µm is of special interest for gas-sensing applications, since numerous rotational-vibrational absorption lines of prominent hydrocarbons like methane, propane, butane or formaldehyde reside in this spectral region. Therefore, compact and robust semiconductor lasers emitting in a single longitudinal mode in continuous wave mode at room temperature are highly desirable for tunable laser absorption spectroscopy. However, the 3 µm to 4 µm spectral range it is not yet completely accessible by common diode lasers or quantum cascade lasers, as long as single mode emitting continuous-wave lasers operating at room temperature are needed. Yet, antimonide-based interband cascade laser structures have meanwhile proven to be a convincing candidate for covering this entire spectral range.

We present systematic design optimizations of interband cascade laser layers to reduce the dissipated threshold power at room temperature with the aim to facilitate high performance room temperature operation. Furthermore, we show that slight variations of the active region design enable us to easily obtain emission in the 3 µm to 4 µm range and beyond. Based on the epitaxial material grown, distributed feedback interband cascade lasers with vertical sidewall gratings are fabricated. We obtain single mode emitting devices operating in continuous wave mode at room temperature, The devices exhibit side mode suppression ratios of~25 dB and typical fine tuning rates of 0.09 nm/mA and 0.3 nm/K. Therewith, the presented devices are ideally suitable for highly sensitive gas sensing of hydrocarbons.

8432-22, Session 5

Near-field characteristics of broad area diode lasers during catastrophic optical damage failure

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One of the key failure mechanisms preventing diode lasers in reaching ultra high optical output powers is the catastrophic optical damage (COD). It is a sudden degradation mechanism which impairs the device functionality completely. COD is caused by a positive feedback loop of absorbing laser light and increasing temperature at a small portion of the active material, leading to a thermal runaway on a sub-nanosecond timescale.

In our experiments we analyze commercial gain-guided AlGaAs/GaAs quantum well broad area diode lasers in single pulse step tests. The near-field emission on the way to and at the point of COD is monitored by a streak-camera combined with a microscope.

In the final phase of the step tests, the power limit for pulsed operation for the diodes is identified as the COD effect occurring at ~50 times threshold current. The near-field before and during COD was resolved on a picosecond time scale. It shows a clear change from a gain to a thermally induced index guided regime at elevated pumping levels. A higher optical load at the facet due to a narrower near-field at constant output power level supports initiation of the COD. The growth of the COD defect site is monitored and a velocity of 30 µm/µs is determined. The final width of the damage is verified by opening the device and taking a micro-photoluminescence map of the active layer. Furthermore the lateral modes redistribute after a primary COD site occurs. This causes a raise of optical load at well separated locations explaining multiple point like damages at the facet. Insight into the physics behind COD is gathered by making up the energy balance.

The experimental data with picosecond time resolution allow a deeper understanding of the kinetics of the COD process connects them with the near-field characteristics at extreme pumping levels.

8432-23, Session 5

Lateral-longitudinal modes of high-brightness inhomogeneous waveguide lasers

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High-brightness edge-emitting lasers ideally would radiate high power and simultaneously have small beam divergence in both directions with respect to the epitaxial growth direction. Large vertical divergence and low lateral beam quality of real broad area ridge lasers are opposed to this ideal due to the typical sub-um vertical waveguide layer and the multitude of guiding lateral modes. A great deal of attention has been focused on developing methods to decrease the vertical divergence and improve the lateral beam quality. Particularly, lasers based on the photonic-band crystal concept and tapered lasers were reported. They allow the mode expansion in the vertical direction and suppression of the higher-order lateral modes, respectively. We present here a novel approach to obtain high lateral beam quality for high-power ridge lasers by employing longitudinal inhomogeneities, which provide lateral mode discrimination. Such discrimination is obtained by means of corrugated shapes of the ridge boundaries. Simulation results for lateral-longitudinal modes of longitudinally inhomogeneous finite-length waveguides are presented. By numerical solution of the wave equation for two-dimensional waveguides, including the output facet, and by calculation of the mode thresholds we show that boundary corrugations cause indeed discrimination of higher-order lateral modes in stripes which are wider than those typically supporting single lateral mode emission. This discrimination is due to higher scattering losses of the higher-order modes into the lateral directions as compared to the fundamental single lobe mode. Thus still for wide stripes the output radiation is expected to be single mode resulting in a high-quality far field with narrow divergence in the lateral direction. Simultaneously, due to the wider stripe width the output emission might have higher power and therefore higher brightness operation can be achieved as compared to a straight stripe without corrugations.

8432-24, Session 5

Spatial rocking for improving the spatial quality of the beam of broad area semiconductor lasers

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``Rocking" is a general effect converting a phase-invariant oscillatory system into a phase-bistable one, where the average phase of the system locks to one of two opposite values.

Many nonlinear systems in nature and technics display self-sustained oscillations with a particular amplitude and an invariant phase. If such system is subjected to an additive signal, then the phase invariance can be broken, and the frequency and phase of the system can lock to that of the external signal. If the complex amplitude of external injection becomes periodic in time or space, then a pair of stable states with equal amplitudes but opposite phases can be obtained. If the system is of sufficiently large aspect ratio, then the rocking implies phase-bistable spatial patterns such as phase-domains, rolls or phase solitons.

In this study we consider theoretically the spatial rocking in broad area edge-emitting semiconductor lasers. Our 2+1-dimensional traveling wave model takes into account the spatio-temporal dynamics of slowly varying complex amplitudes of the counterpropagating optical fields, induced polarizations and carrier densities. The rocking is realized by a periodic in space injection from two, coherently interfering at some angle, beams.

First we show the locking of the phase of emitted beam to one of two opposite values. These two stable states are robust with respect to perturbations of the injected plain wave amplitudes and injection angles. Next, we demonstrate the phase domains and the phase solitons, which are typical rocking-induced spatial patterns. We explore the range of efficient rocking, and conclude that the substantial size of the rocking area in parameter space promises experimental observation of the effect. Finally, we find, that the use of focused injection beams allows to obtain the emission focused in a controllable manner.

8432-25, Session 5

Narrow linewidth discrete mode laser diodes at 1550 nm

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Lasers with narrow linewidth emission are required for a range of applications including ultra-high resolution spectroscopy, sensing, atomic clocks and coherent communications. A major challenge is therefore to produce lasers with the requisite performance at low cost. Discrete Mode Laser Diodes (DMLDs) can be designed for narrow linewidth emission and present an economic approach with a focus on high volume manufacturability of semiconductor lasers. DMLDs are monolithic and can use existing telecommunication laser packaging platforms to produce lasers in high volumes; this is not easily achieved with External Cavity Lasers (ECLs) which have more complex packaging requirements. Monolithic devices also have a lower sensitivity to vibrations and acoustic noise making them attractive for use in harsh environment applications. DMLDs are simple in structure comprising a regrowth-free ridge waveguide Fabry-Pérot laser. The structure of the DMLD presented here was grown by low-pressure metal-organic chemical vapour deposition on a (100) n-type InP substrate. The multiple quantum well active layer consisted of five compressively strained AlGaInAs wells with a well thickness of 5 nm and was designed to achieve a low linewidth enhancement factor over a wide laser temperature range. Single wavelength operation in DMLDs is achieved by introducing index perturbations in the form of etched features positioned at a small number of sites distributed along the ridge waveguide. The spectral linewidth in semiconductor lasers is proportional to the ratio of the spontaneous emission noise to the total photon number in the laser cavity. To increase the photon number in the DMLD we used a relatively long laser cavity of 1000 µm and did not AR-coat the front facet while using a high reflectivity on the back facet to give $\sqrt{(R1R2)} \approx 0.5$.

In this paper we present the static characteristics of narrow linewidth DMLDs and demonstrate linewidths below 100 kHz. The performance of DMLDs is investigated in a Quadrature Phase Shift Keying (QPSK) transmission system operating at baud rates of 10 Gbaud, 5 Gbaud and 2.5 Gbaud. A relatively low baud rate of 2.5 Gbaud was used in the experiment because coherent communication systems have a lower tolerance to laser phase noise at low baud rates. System performance is also investigated using other laser technologies and the DMLD demonstrates comparable performance to that of an ECL with a linewidth of 100 kHz in these experiments. To investigate the system performance for increased linewidths the bias current of the DMLD was decreased to broaden the linewidth and also a DFB with a linewidth of 1.5 MHz was used in the system. Degradation in system performance, particularly at low baud rates, was observed with increased laser linewidths.

8432-26, Session 6

III-N based violet emitting short-pulse diode lasers

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Monolithic multi-section laser diodes (MS-LD) including a saturable absorber (SA) are promising for obtaining extremely short pulses, high peak optical intensity and extremely fast repetition rates in the blue-violet range exploiting either mode-locking or self-pulsating regimes. Recently, 3 ps duration optical pulses have been reported under passive and hybrid mode-locking at 1 GHz repetition rate using InGaN blue-violet LDs [T. Oki et al, Appl. Phys. Express 3, 032104 (2010)].

Here we report MS-LDs that consist of a short reverse-biased SA section and a longer forward-biased gain section. Laser structures with InGaN/InGaN quantum wells (QWs) were grown on c-plane GaN freestanding substrates by metal organic vapor phase epitaxy. After processing, standard cw lasers exhibit threshold and forward voltage of 35 mA and 5V, respectively. Bi-section (SA at the edge) LDs were then fabricated. We will show that the large piezoelectric field that takes place in InGaN/GaN QWs has a profound impact on the laser emission properties while biasing the SA. High-frequency blue laser diodes are achieved with repetition rate in the sub-nanosecond range and pulse length in the picosecond range. Finally, we will discuss laser characteristics that lead to different short-pule lasing regimes, eg. self-pulsation, Q-switching, and Dicke superradiance,

8432-27, Session 6

Laterally coupled high power 2-um GaSb distributed feedback lasers fabricated by nanoimprint lithography

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Single-mode lasers operating within the 2-3 µm wavelength range are useful for many of applications, such as, laser absorption spectroscopy. In particular, distributed feedback (DFB) GaSb-based diode lasers are suitable for sensing of atmospheric greenhouse gasses, since molecules, such as, methane, carbon dioxide and water have strong absorption lines in this wavelength region.

Conventional DFB-lasers, incorporating buried gratings to provide longitudinal mode selection, require epitaxial regrowth, which increases the manufacturing cost and complexity. In addition, due to rapid oxidation of Al-containing layers, the regrowth process is not well-suited for GaSb-based lasers with AlGaAsSb as cladding material. An alternative method for realizing the feedback is to use surface gratings placed on the sides of the laser ridge waveguide during sample processing, forming so called laterally-coupled DFBs. This approach enables fabrication of the semiconductor structures in single epitaxial growth step, thus reducing the cost and alleviating issues related to oxidation of AlGaAsSb layers. The fabrication procedure is flexible and can readily be implemented in various compound semiconductors.

In this paper, we report a process for fabricating GaSb-based laterally-coupled DFB-lasers exploiting nanoimprint lithography for defining the ridge waveguide and the grating. This technology addresses issues related to mass fabrication and cost of the DFB-lasers. We demonstrate devices on a range of wavelength from 1997 nm to 2036 nm. These lasers exhibit single-mode operation with a SMRS of more than 55 dB and high output power of 14 mW.

8432-28, Session 6

Band engineering of dilute bismide alloys for efficient near- and mid-infrared semiconductor lasers

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Despite their importance in optical communications, InP-based lasers in the 1.3-1.6 micron range suffer from high threshold currents and a large sensitivity to temperature, requiring the use of energy-demanding temperature stabilisation. Previous works have shown that Auger recombination processes involving carrier excitation to the spin-split-off (SO) band dominate the threshold current of such lasers around room temperature. Surprisingly, antimonide-based lasers operating at 2-3 microns have lower threshold currents and a reduced sensitivity to temperature. This is because the large SO splitting in antimonide alloys (such that the SO splitting exceeds the band gap) suppresses such losses. The SO splitting is always less than the energy gap in conventional alloys at telecomm wavelengths. However, replacing arsenic by bismuth in GaBiAs can lead both to a rapid increase in SO energy and reduction in the energy gap. Photoreflectance measurements show the SO energy exceeds the energy gap for Bi fractions ~ 10%. The incorporation of bismuth in GaAs is predicted to lead to a band-anticrossing (BAC) effect (in the valence band) causing a large band gap bowing. Tight-binding calculations confirm that the observed strong variation of the band gap and SO energy with Bi composition are well described by a BAC interaction between the extended states of the GaAs valence band edge and highly localized Bi-related defect states in the valence band. We extend these calculations to consider GaBiNAs alloys. We show that Bi and N largely act independently of each other. Since bismuth principally influences the valence band, and nitrogen the conduction band, combining bismuth and nitrogen in III-V alloys offers huge potential for engineering the conduction and valence band offsets, the band gap and spin-orbit splitting, with wide scope for the design of photonic devices, including loss-free lasers in the telecomms band, with potential as efficient, uncooled sources.

8432-29, Session 6

Narrow linewidth 1120-nm GaInAs/GaAs VECSEL for cooling Mg+ ions

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Optical frequency metrology and quantum information processing use frequency-stable narrow linewidth lasers for laser cooling and trapping of atoms or ions. These lasers operate in resonance with atomic transitions and require linewidths that are close to, or below, the linewidth of the optical transition (typically few MHz). We have developed a prototype of an optically-pumped narrow linewidth vertical external cavity surface emitting laser (VECSEL) to be used for cold atom/ion quantum research and to help spawn commercial products requiring similar laser characteristics. The VECSEL gain mirror is designed for emitting frequency doubled light at around 560 nm, which can be further doubled to 280 nm resonance of Mg+ ions.

The gain mirror is based on GaInAs/GaAs material system with highly compressively strained quantum wells. The compressive strain of the quantum wells is compensated with tensile strained GaAsP layers in order to preserve high crystal quality. The gain mirror was grown by solid-source molecular beam epitaxy in a top-emitting geometry. An intra-cavity diamond was used as a heat sink.

VECSEL operation was demonstrated close to the desired wavelength of 560 nm. The wavelength tuning and linewidth characteristics were, however, examined at the fundamental wavelength of 1118.5 nm. During the wavelength tuning experiment, the laser mode hopped with a step of around 7.6 pm. It is unclear whether the jumps are just measurement artifacts or true wavelength jumps since the resolution of the wavemeter used for the measurement coincided with the magnitude of the jumps. For an output power of 0.8 W (pump power 9 W) we have measured a linewidth of less than 300 kHz as determined by a beat measurement between the VECSEL and a commercial fiber laser. In the future, the laser cavity will be improved in order to demonstrate stable, narrow linewidth operation at the frequency doubled wavelength.

8432-30, Session 6

Frequency doubled AlGaInP-VECSEL with high output power at 331 nm and a large wavelength tuning range in the UV

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Since their invention, vertical external cavity surface-emitting lasers (VECSELs) have aroused growing interest in science. The tremendous advantage of the external cavity is the usage of intra-cavity elements to increase the VECSEL's capabilities and therefore widen the range of applications in spectroscopy, biophotonics or even lithography. Tuning of the resonance wavelength can be established by using optical elements like birefringent filters. Furthermore, by using frequency doubling crystals intra-cavity second harmonic generation opens up the way to additional wavelength ranges, which are not directly reachable.

We present an optically pumped VECSEL system based on a multi-quantum-well structure with 20 compressively strained GaInP quantum wells (QWs) for an operation wavelength of around 660 nm. Ten QW pairs are placed in $(Al_{0.55}Ga_{0.45})_{0.51}In_{0.49}P$ cladding layers in a resonant periodic gain design. The QW pairs are embedded in $(Al_{0.33}Ga_{0.67})_{0.51}In_{0.49}P$ barriers. The active region is fabricated on a 55 $\lambda/4$ pairs $Al_{0.50}Ga_{0.50}As/AlAs$ distributed Bragg reflector. Continuous-wave operation is made possible by bonding a single crystal diamond plate on top of the metal-organic vapour-phase epitaxy fabricated VECSEL chip.

By using an intra-cavity birefringent filter and a beta barium borate non-linear crystal, we are able to present a wavelength tunable UV-VECSEL at a wavelength of around 330 nm. Tuning ranges around 7 nm in the UV spectral range can be shown. The output power of the UV-VECSEL could be increased to >100 mW at a wavelength of 331 nm.

8432-31, Session 7

Theoretical modeling of mode-locked quantum dot lasers

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Monolithic passively mode-locked semiconductor lasers are compact sources of picosecond and subpicosecond pulses with high repetition rates suitable for applications in telecommunication technology. Recently a new promising generation of mode-locked semiconductor lasers based on quantum dot materials was developed. Although, these lasers demonstrate numerous advantages over conventional quantum well devices, such as low threshold currents, small alpha factors, low pulse chirp, high temperature stability, optimization of performance of quantum dot mode-locked lasers for specific applications is still a challenging task. Such optimization is hardly achievable without comprehensive mathematical modeling of the complex nonlinear dynamical regimes in these lasers. Here we present the results of theoretical studies of several modifications of models of quantum dot mode-locked lasers based on delay differential equations (DDE). Being much simpler than the conventional traveling wave models, these equations enable a detailed bifurcation analysis and in certain cases analytical investigations of mode-locked solutions. Using those DDE models we performed numerical and analytical studies of the effects of carrier exchange between the wetting layer and discrete levels in quantum dots, as well as those of external parameter modulation and external coherent injection on the operation regimes and pulse characteristics of mode-locked quantum dot lasers. Asymptotic approaches for estimation of the locking range half-width in hybrid mode-locked laser and in a mode-locked laser with a coherent single frequency injection are described. The effect of delayed feedback on mode-locked regimes in a monolithic laser is discussed. Bifurcation analysis of different operation regimes is performed with the help of path following software package DDEBIFTOOL. A comparison revealed a good qualitative agreement between the results of the DDE modeling with those obtained with the help of traveling wave equations.

8432-32, Session 7

Passively mode-locked 1-GHz MOPA system generating sub-500-fs pulses after external compression

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We compared the performance of DQW and TQW edge-emitters in a purely passive mode-locked 1GHz MOPA system at 1075nm wavelength. The main purpose of our research was to generate a 1GHz pulse train of sub-500-fs pulses with an average power near 1W.

The master oscillator consists of an 800µm long diode laser with an integrated 100µm saturable absorber section. To achieve a repetition rate of 1GHz the laser is embedded in an external resonator formed by one external mirror of 30% reflectivity and the uncoated laser facet with 35% reflectivity. The epitaxial structure of gain and absorber section is equal. Passive mode-locking is induced by applying a reverse DC voltage to the absorber section. We tested and compared DQW and TQW versions of the oscillator finding that for TQW lasers higher absorber voltages (5 - 8V) are necessary to enforce fundamental mode-locking than for DQW lasers (4.5 - 5.0V). However, DQW diodes tend to produce satellite pulses at high gain currents.

Using a tapered amplifier the average power is increased to 0.9W. The 6mm long DQW and TQW amplifiers consists of an index-guiding waveguide section and a gain-guided tapered section. After the TQW amplifier we observed significant ASE and even laser emission. With a DQW amplifier the output of the MOPA system was free of strong ASE or laser emission.

During the amplification we observed a significant narrowing of the spectrum. We attribute this to the interaction of fast gain saturation and the pulse chirp. A FROG analysis shows that the spectral phase remains undisturbed by the amplifier chain.

After compensation of the linear chirp in a grating compressor we create a pulse of 342fs duration. We found that the oscillator gain current and the absorber bias voltage have significant impact on the pulse duration.

8432-33, Session 7

Mode-locking behaviour in an InAs/InP quantum dot laser with dual spectral lobes

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The gain behaviour and optical spectral characteristics of quantum-dot lasers exhibit a number of unique features that are substantially different from what measured in QWs or bulk gain media. In particular, the splitting of the ground state into two discrete sub-bands and the consequent appearance of two sets of modes in the optical spectrum has been recently investigated by a number of groups. Although the precise physical origin of this phenomenon is still not completely clear, its impact on the dynamical behaviour of a laser under mode-locking operation is of great interest. In fact, depending on the biasing conditions of the device, the laser exhibits stable mode-locking operation on one of the two sets of modes only or on both sets simultaneously. In the latter condition, the two spectral lobes can either be locked together, thus generating extremely narrow pulses over a very large spectral bandwidth, or the laser can emit two pulse trains with distinct repetition rates.

In this paper we investigate the mode-locking behaviour and the lasing dynamics of QD mode-locked lasers with integrated saturable absorbers. The devices were fabricated on a material with five layers of InAs quantum dots embedded in an InGaAsP matrix emitting at a wavelength around 1550 nm. A full understanding of the pulse formation and locking behaviour is obtained through the use of a sonogram technique that can unambiguously retrieve both the phase and time profiles of low-energy pulses. We show that for a certain range of biasing condition, it is possible to lock the two sets of modes together up to a separation of 15 nm between the spectral peaks. Under these conditions, the generated pulses exhibit a weak red chirp with higher order components and the temporal duration can be as low as 700 fs.

8432-34, Session 7

Conversion between optical ASK and optical FSK using nonlinear dynamics of semiconductor lasers

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Due to the continuous demand in transmission capacity and distance, many advanced optical modulation formats have been proposed to substitute for conventionally adopted amplitude-shift keying (ASK), including frequency-shift keying (FSK) and phase-shift keying (PSK). Therefore, different optical modulation formats would be adopted for different optical communication networks in the future depending on their scales and applications. Accordingly, optical modulation format conversion becomes a key functionality bridging different optical networks. In fact, many conversion schemes based on different device nonlinearities have been proposed over the past years, which however focus mainly on conversion from ASK to PSK. In this study, we propose

to use the period-one (P1) nonlinear dynamics of semiconductor lasers for optical modulation format conversion between ASK and FSK. When a semiconductor laser is subject to an incoming optical carrier, equivalently an external optical injection, it can enter, under proper injection conditions, into P1 dynamics through Hopf bifurcation due to the radical modification in field-carrier coupling of the injected laser resulting from the dynamical competition between injection-imposed laser oscillation and injection-shifted cavity resonance. Equally-separated spectral components appear, of which intensity and frequency depend strongly on the injection level and frequency. This suggests that a dynamical amplitude or frequency variation of the incoming optical signal, such as ASK or FSK, respectively, would lead to corresponding dynamical variation in amplitude and frequency of each spectral component. Therefore, by properly selecting the optical frequency of the output optical carrier and by minimizing the residual ASK and FSK modulation, both ASK-to-FSK and FSK-to-ASK conversions can be achieved, where bit-error ratio down to 10-12 is achieved with a slight power penalty. Only a typical semiconductor laser is necessary as the key conversion unit. In addition, different output modulation depths and different frequency shifts of the optical carrier can also be achieved. The latter allows a simultaneous frequency conversion of the optical carrier if required. These characteristics may increase the flexibility and re-configurability of the proposed system.

8432-35, Session 8

Square-wave switching in orthogonal polarization delay-coupled semiconductor lasers

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We will report numerical and analytical and experimental studies of two edge emitting lasers coupled through their normally non-lasing polarization modes. The main goal is to characterize the square wave polarization switching dynamics. We examine the possible steady states available to the system and their bifurcations to locate the source and the mechanism of square waves. We show the complicated overlap of several attractors, periodic and chaotic in the case when both polarizations are active. We have found two types of square-wave switching, one in which the intensities of the polarizations do not reach zero at any time during the oscillations, and another in which, when the intensities are at the off state, they approach zero within the limits of spontaneous emission. The first type appears to be stable can exhibit symmetric or asymmetric features and are numerically stable and occur in a very small range of parameter region. The second type occurs in a wide parameter regions and is transient that decays towards a steady state in which the laser emit orthogonal polarization light. We will also present similar results using two VCSELs coupled with orthogonal rotated polarization delay terms when emit only in the x or y polarization when not coupled. We will show similar results of transient and stable square wave dynamics over regions of parameters, the steady states and also the possible bifurcations. We report on extensive experimental results for both systems of lasers and their comparisons with the numerical and analytical results.

8432-36, Session 8

Theoretical analysis of a multi-stripe laser array with external off-axis feedback

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During last decades high power laser diodes attracted much attention of researchers due to their applications in different areas such as medicine, spectroscopy and material processing. However, because of transverse instabilities arising at sufficiently high pump levels these lasers usually demonstrate poor beam quality caused by large far-field divergence. Furthermore, in the absence of spectral filtering they usually operate in unwanted dynamical periodic or chaotic states. Hence, improvement of performance of these lasers is a very important task. Several approaches have been developed to improve the beam quality and increase brightness of high power laser diodes. One of these approaches, which was recently studied experimentally [1], is based on the use of multi-stripe laser array with filtered off-axis feedback. In the present work we perform a theoretical investigation of such kind of multi-stripe semiconductor laser arrays and also analyze a method of improving output beam characteristics of a broad area laser with the help of an external tilted V-shaped cavity. We demonstrate that the tilted feedback enforces a spatial phase coupling between different points in the laser transverse section, hence selecting and stabilizing a single transverse supermode, which corresponds to a high power, high brightness plane wave traveling in the extended cavity. We derive and study a reduced model of a multi-stripe array with off-axis feedback - a set of three delay differential equations for the electric field envelope, homogeneous component of the carrier density and the transverse carrier grating. Bifurcation analysis of this system reveals the existence of multimode self-pulsing instability leading to a periodic and irregular time dependence of the output intensity. The results obtained using the reduced system are in agreement with those of 2+1 dimensional traveling wave model with diffraction, gain dispersion, and carrier diffusion in the semiconductor medium being taken into account.

[1] A. Jechow, M. Lichtner, R. Menzel, M. Radziunas, D. Skoczowsky, and A.G. Vladimirov, “Stripe-array diode-laser in an off-axis external cavity: Theory and experiment,” Optics Express 17, 19599-19604 (2009).

8432-37, Session 8

Low-frequency fluctuations in a laser diode with phase-conjugate feedback

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Optical chaos is easily observed in a laser diode with either conventional (COF) or phase-conjugate optical feedback (PCF). We focus here on the so-called chaotic low-frequency fluctuations (LFF) where the laser exhibits slow power dropouts together with fast picosecond dynamics. LFF have been largely studied in the case of COF, where they originate from a sequence of bifurcations on a large number of so-called external cavity modes [1]. By contrast, to our knowledge there is no experiment analysing LFF in the case of PCF. The laser dynamics is known to be quite different from the case of COF [2] and the bifurcations leading to LFF remain to be elucidated. We report here on a systematic study of LFF in a laser diode with PCF. PCF is obtained by four-wave mixing in a SPS photorefractive crystal using a self-pumped ring-cavity. Qualitatively different dynamics are observed by increasing the phase-conjugate mirror reflectivity or the injection current level. A combination of spectral and temporal measurements unveils the transition to LFF dynamics. The statistical properties of the time between power dropouts (mean and standard deviation) are studied as a function of the laser and feedback parameters. These LFF properties are then contrasted with those known for laser diodes with COF. Interestingly, the phase conjugation build-up time here in SPS is around 1 ms, hence is three orders of magnitude faster than what has been reported in previous dynamical studies of chaos in lasers with PCF using BaTiO3 photorefractive crystals [3]. How the phase conjugation time-scale impacts on the laser dynamics remains an interesting question to which we contribute here. [1] A. Hohl et al., Phys. Rev. Lett. 82, 1148 (1999) [2] T. Erneux et al., Phys. Rev. E 68, 066205 (2003), [3] J. S. Lawrence et al., Phys. Rev. A 63, 033805 (2001).

8432-38, Session 8

Photonic single nonlinear-delay dynamical node for information processing

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Optical information processing of high-speed signals is a challenge in future photonic networks. Computational methods based on the transient response of a complex dynamical system to an input, such as reservoir computing, are very promising for processing high bit-rate data streams. In these methods the dynamical input signal is mapped onto a high-dimensional state space. In classical reservoirs the networks are composed of a large number of randomly interconnected nodes, receiving input signals. The output layer is a linear weighted sum of the node states. Linear regression is used to optimize the weights. Photonic implementation of reservoir computing is highly desirable. However, a high number of nodes impose major restrictions and challenges for a technological implementation. These constraints can be overcome by replacing the complex network by a single nonlinear element subject to delayed feedback [1] with the network nodes distributed along the delay line.

In this work we perform numerical simulations to show that a reservoir based on a laser diode subject to delayed feedback with Ikeda-like nonlinear dynamics possess universal computational capabilities. This system can be implemented by using a laser diode, a Mach-Zehnder interferometer and a fiber delay line. Without input the laser operates in a stable state. When excited by an input data stream the laser exhibits complex transient dynamics that is used for computation.

We have found that this laser system has the properties of standard reservoirs: short-term memory capacity, separation property and generalization capability. We have also analyzed the computational power of the system for several benchmarks such as delayed 5-bit parity task, time series prediction for Lorenz chaotic system and NARMA task. The obtained performances are comparable to or overcome those of state of the art traditional neural networks and classical reservoir computing.

[1] L. Appeltant et al., Nature Commun. 2, 468 (2011).

8432-39, Session 8

Dynamical properties of two delay-coupled lasers: on spectra, correlations, and synchronisation

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The dynamical and synchronisation properties of delay-coupled semiconductor lasers have found considerable interest over the past 10 years. Phenomena like delay-induced instabilities, zero-lag synchronisation and generalised synchronisation have been found depending on the coupling configuration. In order to gain a better understanding of these phenomena we numerically and analytically study the dynamics of two semiconductor lasers which are delay-coupled via a semitransparent mirror. We vary the transmission and reflection of the mirror, while keeping their sum constant. For equal transmission and reflection of the mirror, the lasers show identical chaos synchronisation. If the reflection is zero, the lasers show generalised synchronisation of leader-laggard type with no correlation at zero-lag, and only high correlations at time shifts corresponding to multiples of the delay time. Setting only the transmission to zero results in uncoupled delay dynamics.

We study the transition between these types of dynamics via autocorrelation and spectral properties. As the system evolves from uncoupled dynamics to identical synchronisation, the dynamics of the individual elements does not change significantly, but the crosscorrelation function increases with crosscoupling. As the lasers evolve from identical to generalised synchronisation, some extrema disappear in the correlation functions, while new maxima appear in the spectral density.

To interpret this dynamical behaviour, we replace the lasers by delay-coupled linear stochastic maps. This allows to compute the correlation functions and spectral densities analytically. We find that both the spectrum and the correlation of the coupled system can be written as the average of two single units: one with a constant positive feedback, corresponding to the synchronisation manifold, and one with a feedback depending on the mismatch between self- and crosscoupling, corresponding to the 'transverse dynamics'. The linear relation for correlation and spectra of coupled stochastic maps is shown to be an excellent approximation for the laser dynamics, and even becomes exact in the limit of face-to-face coupling.

8432-40, Session 9

Higher-order photon correlations in pulsed photonic crystal nanolasers

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We report on the higher-order photon correlations of a high-β nanolaser under pulsed excitation at room temperature. Using a multiplexed four-element superconducting single photon detector we measured g(n)(~0) with n=2,3,4. All orders of correlation display partially chaotic statistics, even at four times the threshold excitation power. We show that this departure from coherence and Poisson statistics is due to the quantum fluctuations associated with the small number of dipoles and photons involved in the lasing process.

8432-41, Session 9

Excitability in a monolithic vertical cavity laser with saturable absorber

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We show that a monolithic and compact vertical cavity laser with intracavity saturable absorber can emit sub-nanosecond duration excitable pulses. The observation is made thanks to an original design of an optically-pumped VCSEL that allows monolithic integration of a saturable absorber inside the active zone of the cavity.

Excitability is a general non-linear dynamical mechanism characterized by : i) a threshold in the response to an input perturbation leading to a "all or nothing" type of response and ii) appearance of a calibrated response above threshold. Excitable response is present in biological (neurons), chemical and physical systems and is believed to have a huge potential for photonic applications such as clock recovery, pulse reshaping, optical delay lines, or innovative all-optical signal processing (reservoir computing, excitable logic-gates).

Depending on the phase portrait that leads to this qualitative behaviour, different classes of optical excitable systems have been identified. Excitability in our system presents two main advantages over other kinds of optical systems where excitability has been demonstrated. Firstly, the pulse duration is governed by the carrier recombination time in the active zone which can potentially reach sub-ns timescales (~0.7ns here). Secondly, no coherent light injection or holding beam is necessary to achieve excitability, which arises as a competition between gain and saturable absorption, hence a simpler and more compact system.

Experimental results are compared to a model, including the effect of noise [1]. Finally, we present experimental results obtained in arrays of micropillar cavities towards the demonstration of nonlinear wave propagation.

Reference :

[1] S. Barbay, R. Kuszelewicz, A. Yacomotti, to appear in Opt. Lett. (2011).

8432-42, Session 9

Bifurcations in a two-color laser subject to dual optical injection

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Optical injection of laser diodes, which gives rise to a range of nonlinear phenomena including chaos and multistability, has been studied extensively for the single mode laser. Dual-mode lasers, that include vertical cavity surface emitting lasers (VCSELs), ring lasers, photonic crystal lasers, and two color Fabry-Perot (FP) lasers, subject to a single optical injection have recently been investigated due to potential applications in all-optical signal processing.

In this work, we examine both theoretically and experimentally a two color FP laser subject to dual optical injection into each of the lasing modes. The device we consider is a two color FP which has been specifically designed to support two longitudinal modes that are separated by ~0.5 THz. The large mode spacing results in a weak coupling between the modes and are therefore stable, which is in contrast to VCSEL and ring lasers. The dynamics of this system can be modeled using the 5-dimensional rate equation model and includes a nonlinear gain that accounts the cross and self saturation. Our rate equations include two injected fields into the two modes, with amplitude K1, K2 and detunings $\Delta\omega 1$, $\Delta\omega 2$, and we analyse the bifurcations using the continuation tool AUTO-07p.

Our model allows us to identify a number of regions of multistability, which we describe in terms of their bifurcations. In the K1-K2 plane with $\Delta\omega 1=\Delta\omega 2=-18$ GHz , the saddle-node bifurcation (SN) is almost circular. On decreasing $\Delta\omega 1$ the SN deforms and at $\Delta\omega 1=-12$GHz a swallowtail bifurcation is born and creates a triangular region, delimited by two cusp bifurcations, where both lock states coexist giving rise to a bistability between the locked states. We demonstrate this bistability of locked states experimentally and show that it can be used as the basis for an all-optical memory element with improved switching performance. We highlight a bistability between a locked states and limit cycle that is the result of the dual injection and is not present in the limit of a single injection.

We will also discuss the limits of the bifurcation parameters that result in the bistability of locked states and switching. We will also extend this to standard FP lasers and demonstrate that the bistability of locked states can be generalised to a FP laser with dual optical injection for longitudinal mode spacings between 0.2-1.0 THz.

8432-43, Session 9

Mapping transients in the nonlinear dynamics of an optically injected VCSEL

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Optical injection is one of the key methods for invoking nonlinear dynamical outputs in laser systems. Optically injected laser systems based on solid state lasers, both micro-chip and macroscopic-crystal-based; edge emitting semiconductor lasers of various types; and VCSELs have been studied. The system parameters that are used to control the nature of the output from an optically injected laser system are the injection strength and the frequency detuning between the optical frequency of the free running master and slave lasers of the system. A map of the dynamics can be generated using a number of measurands to facilitate identifying the fundamentally different dynamical regions in the injection strength/frequency detuning parameter space (see as examples: I. Gatare, M. Sciamanna, M. Nizette, H. Thienpont, and K. Panajotov, "Mapping of two-polarization-mode dynamics in vertical-cavity surface-emitting lasers with optical injection," Phys. Rev. E 80, 026218 (2009); J. P. Toomey, D. M. Kane, S. Valling, and A. M. Lindberg, "Automated correlation dimension analysis of optically injected solid state lasers," Opt. Express 17, 7592-7608 (2009); K. Schires, A. Hurtado, I. D. Henning, and M. J. Adams, "Polarization and time-resolved dynamics of a 1550-nm VCSEL subject to orthogonally polarized optical injection," IEEE Photonics Journal 3, 555-563 (2011)). It is the 1550 nm VCSEL system described in the third of these references that is relevant to the current study. Its data has been analysed previously and maps have been generated which show the boundaries between of the basically different dynamic regions, including stable injection locking, limit cycle or period-1, period doubling and chaos. It is emerging as a general feature of optically injected laser systems operating in nonlinear dynamic regimes that their nonlinear dynamics are subject to instability and non-stationarity in certain regions of the dynamic map. Herein we describe a set of automated algorithms used to establish several measures to identify transients and instabilities in the nonlinear dynamical output of an optically injected VCSEL for set and unchanging driving parameters. Thus, a map of non-stationary dynamical regions can be generated and correlated with the nature of the dynamics observed in these regions. Injection of light polarised orthogonally to the "natural" polarisation of the slave laser is found to cause more instabilities in the nonlinear dynamics than "matched" polarisation injection, and it is this case that is studied in most detail. Average intensity and RMS amplitude measurements are used to determine parameters where the laser is injection locked so that this stable, CW region can be eliminated from consideration. The significance of the instabilities in the nonlinear dynamical outputs from the perspective of applications will also be discussed.

8432-57, Poster Session

Theoretical study about the optical gain in indirect bandgap semiconductor cavities

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Silicon has been considered unsuitable for optoelectronic applications owing to its indirect bandgap, which limit its efficiency as light emitter. An extensive set of studies have proposed the use of cavities to increase the emission of light as a consequence of the Purcell effect. In a recent study [N. D. Lanzillotti-Kimura et al., Phys. Rev. Lett. 104, 187402 (2010)] a Purcell-like effect was observed for phonon emission, extending the concept from the electromagnetic to the acoustic field. In this work, we consider an indirect-bandgap-semiconductor (IBS) cavity, where the photons and phonons can be confined, which can be achieved by placing a THz-phonons cavity inside a photonic cavity. We obtain a theoretical expression of the Purcell factor for the phononic cavity. Finally, we get that the optical gain of the IBS cavity is proportional to the product of the phononic and photonic Purcell factors. This gain could overcome the main losses mechanism in the cavity (free-carrier absorption) at room-temperature, which could facilitate lasing emission.

8432-59, Poster Session

Performance and electrical consumption evaluation of semiconductor optical amplifier

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The electrical consumption of the devices becomes an important parameter in the design of optical transmission systems. For a given performance, the component consuming the weakest energy will be preferentially chosen by system manufacturers. Semiconductor based components are widely used for active function realization (light source, amplifier, optical receiver,...) and we know that performances of these devices can strongly be affected by temperature variation. Therefore, most of them need to be cooled and an important part of the whole power consumed by the optical module is used by thermo-electronic cooler and associated electronics. In this paper we propose to study the energy consumption in an optical module as function of its environmental conditions.

We have measured the gain of a semi-conductor optical amplifier (SOA) at different temperature of the chip and in a varying temperature environment. The temperature of SOA is controlled thanks to a thermal sensor placed close to the chip and a Peltier cooler (or heater) beneath the SOA submount. SOA is optically coupled to a fiber and all these elements are fixed in a butterfly type packaging. The SOA module is put in a hermetic oven for the control of the environment temperature. The temperature of the oven has been varied between 20 and 80° as well as the chip temperature. For all measurement, we register the electrical power consumed by the peltier system for the temperature of the chip.

Measurement show an excellent behavior of our SOA when chip temperature increases. A degradation of 8 dB is measured when SOA temperature increases from 20 to 80°C whatever are the current of polarization of SOA or the oven temperature. These results will be discussed in details in the paper as well as the gain peak wavelength and optical bandwidth of the SOA when temperature increases. Electrical power consumption evolution as function of oven temperature has also been investigated. An optimization between gain of SOA and power consumption will be presented.

8432-60, Poster Session

Numerical analysis of hybrid mode-locking in edge-emitting quantum-dot semiconductor lasers

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The advantages of self-assembled quantum dot (QD) materials can be exploited in multisection mode-locked lasers which are able to generate stable high intensity picosecond and sub-picosecond pulses. Short mode-locking (ML) pulses with a repetition rate inverse proportional to the cavity round trip time can be generated in two-section edge-emitting devices which consist of a reverse biased saturable absorber and forward biased amplifying sections. It is well known, that the quality of ML pulses can be improved substantially with the help of hybrid ML technique based on periodic modulation of the reverse bias applied to the absorber section. If the modulation frequency is sufficiently close to the repetition frequency of free running passively mode-locked laser, it can entrain the frequency of pulsations. As a result of this entrainment a considerable narrowing of ML spectral line in radio-frequency spectra and, consequently, a significant reduction of pulse time jitter take place.

Simulations of hybrid ML in QD lasers have been performed using two different approaches, one of them based on the traveling wave (TW) equations and another based on the delay-differential equations (DDE) model proposed in our recent publications. In both these models the reverse bias modulation was described by a periodic variation of the carrier relaxation rate in the absorber section. In addition, the DDE model was subjected to a bifurcation analysis with the help of the software package DDE-BIFTOOL, which allows numerical continuation of locked solutions in parameter space. The locking cones where the pulse repetition rate is entrained by the external modulation frequency are calculated on the plane of two parameters, modulation amplitude and frequency detuning, and the dependence of the locking range half-width on different laser parameters is discussed. Finally, we demonstrate that the hybrid ML regime can be also achieved in the case when the voltage modulation frequency is approximately twice higher or lower than the pulse repetition rate of the free running passively mode-locked laser

8432-61, Poster Session

Self-consistent simulation of mid-IR quantum cascade lasers based on rate equation approach

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The Quantum cascade lasers (QCLs) have been focus of much research since they have been demonstrated in 1994 [1]. The experimental development has stimulated interest in theoretical work aimed at explaining physical processes involved in their operation. Typically there are two approaches for modelling of such devices, non-equlibrum Green's function method and Monte Carlo method. Applying these methods provides deep insight into the principles of carrier transport in devices but requires large computational efforts which make them difficult to be applied as a tool for optimization of practical devices. In this work we have adopted the other approach based on self-consistent solving of Schrödinger equation, Poisson equation and rate equations for active region and injector. This approach is much less demanding in terms of time and computational power. We have developed a QCL simulator that calculates the carrier distribution, band profile, transition rates, electron temperature and gain [2]. Due to the inclusion of photon rate equation the above threshold characteristics of the lasers can be evaluated. The simulator takes into account all relevant scattering mechanisms, i.e., LO-phonon scattering, electron-electron scattering and accounts for band nonparabolicity. The approach has been used to optimize technology of mid-IR QCLs. The calculated current-voltage (I-V) characteristics and light-current (L-I) characteristics were directly compared with experiment. All simulations show the feasibility of this approach in providing better understanding of the physics of QCLs as well as for optimizing of device design.

[1] J. Faist, et al, Science, vol. 264, 553 (1994)

[2] P. Karbownik, et al, IV Workshop on Physics and Technology of Semiconductor Lasers, Kazimierz Dolny, 23-26.10.2011

8432-62, Poster Session

Nonlinear dynamics in directly modulated semiconductor ring lasers

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Semiconductor ring lasers (SRLs) are very attractive devices in photonic integrated circuits because of the possibility of encoding digital information in the direction of emission. The bistability between the two counter-propagating modes leads to a much richer dynamical behaviour than commonly found in other types of semiconductor lasers. In this work, we have theoretically studied the dynamical behaviour of current modulated SRLs. As we vary the amplitude and frequency of the modulation around a fixed bias current, different dynamical states including periodic, quasi-periodic and chaotic states are found. As in other single mode semiconductor lasers, the modal intensities in a SRL present chaotic behaviour for driving frequencies comparable to the relaxation oscillation frequency. In this regime the two counter-propagating modes vary in phase. However, for modulation frequencies significantly lower than the relaxation oscillation frequency, we reveal the existence of chaotic oscillations where the two counter-propagating modes are in anti-phase. In order to get a more complete understanding of the dynamics of SRLs at low modulation frequencies, we derive a reduced model using asymptotic methods. This reduced model uncovers a topological resemblance between current-modulated SRLs and the periodically driven Duffing- Van der Pol oscillator.

8432-63, Poster Session

Experimental and numerical study of square wave oscillations due to asymmetric optical feedback in semiconductor ring lasers

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We study experimentally and numerically a new dynamical regime in the operation of semiconductor ring lasers (SRLs) subject to long delayed optical feedback. When employing an asymmetric feedback scheme, we find experimentally that the SRL can show square-wave intensity oscillations with a 50% duty cycle. In this scheme, where the output in the one direction is delay coupled to the other direction but not vice versa, the laser switches regularly between the clockwise (CW) and counterclockwise (CCW) propagating modes. The measured period of the square-waves and is slightly longer than twice the roundtrip time in the external cavity. We analyze the regularity and the shape of the square-waves as a function of the pumping current and the feedback strength. Higher pump currents on the SRL lead to lower duty cycles of the square waves, while the period of the waveform remains the same. At higher feedback strengths, on the other hand, we observe square waves with irregular duty cycle, and then more complex waveforms. To understand the origin of these dynamical regimes, we rely on numerical simulations based on the Lang-Kobayashi equations. We demonstrate a novel mechanism leading to square wave oscillations based on the cross-feedback overcoming backscattering asymmetries present in the device's structure. Our numerical results are in close agreement with the experimental ones.

8432-64, Poster Session

Electrical and optical characterisation of mid-IR GaAs/AlGaAs quantum cascade lasers

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The GaAs/AlGaAs quantum cascade lasers (QCLs) are important infrared light sources with various applications in defense and civilian fields. Their application is however limited by degradation of performance characteristics induced by the strong heating of their active regions. Therefore, thorough optical and electrical characterization is required to understand and resolve these limitations. Temperature dependent Light-Current-Voltage (L-I-V) characteristics of GaAs/AlGaAs QCLs operating up to room temperature in pulse mode are reported. The QCLs were developed at the Institute of Electron Technology. Devices emit at around 9.4 µm. The temperature influence on optical and electrical performance of the QCLs with respect to the output power, slope efficiency, threshold current/voltage, turn-on voltage, characteristic temperatures T0 and T1, and waveguide losses are investigated systematically. The rollover observed in (L-I-V) curves, is explained in terms of two effects, the thermal rollover (the positive feedback loop between increasing laser core temperature and threshold current density) and Stark-shift in the conduction band structure. In addition, the influence of different mesa dimensions on the QCL parameters is analyzed. Experimental results clearly indicate that among the examined geometries the 25µm wide mesa devices exhibit the best operational parameters i.e., the highest Tmax and T0, highest wall-plug and slope efficiency, as well as a small thermal resistivity and the smallest temperature increases in the active area. The knowledge of the above parameters is crucial for designing GaAs/AlGaAs-based devices for high temperature CW operation.

8432-65, Poster Session

Low timing jitter 40 Gb/s all-optical clock recovery based on an amplified feedback laser diode

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We demonstrate 40 Gb/s all-optical clock recovery by using a monolithic integrated amplified-feedback laser (AFL) with coherent injection-locked method. The AFL consists of a gain-coupled DFB laser and an optical amplified feedback external cavity. With proper design and operation of AFL, the device can work at self-pulsation state that resulted from the beating between two lasing modes. The self-pulsation can be injection-locked to the optical clock embedded in input data streams. Due to different work mechanisms, there are two all-optical clock recovery operation modes: incoherent injection-locked and coherent injection-locked. It's predicted that the coherent injection method has various advantages: 1) requiring low injection power recovery, 2) independent of the bit rate and 3) introducing little timing jitter to the recovered clock. The robustness of coherent clock recovery is confirmed by our experimental results. We set up a return-to-zero (RZ) pseudorandom binary sequence (PRBS) data streams all-optical clock recovery system. The performance of the AFL based all-optical clock recovery is characterized by the dependence of the timing jitter of the recovered clock on the optical signal noise ratio (OSNR), chromatic dispersion (CD), optical power, wavelength and frequency of the injected signal. The timing jitter of recovered clock is kept below 200 fs when OSNR decreased from 45 dB to 20 dB, and kept less than 400 fs even with OSNR as low as 7 dB. Besides, stable clock with timing jitter around 200 fs is extracted clearly when chromatic dispersion changed from 0 ps/nm to 408 ps/nm. The scheme still works even when the injection power is reduced to -20 dBm, which means the recovery sensitivity is very high. We also found that the wavelength tolerance is 0.07 nm, frequency-locking range is bout 190 MHz. We believe that these results are key information that would be of interest to the research community.

8432-66, Poster Session

Interaction between laser beams FP and BFB laser diodes

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Possibility to influence properties of one laser beam with the help of the other ones is the promise procedure for the design of optical switches, optical sensors, laser beams former, etc. We have used two different laser sources - stable true single mode DFB laser at the wavelength of 1550 nm and FP laser with several longitudinal modes working at the same wavelength. Several experiments have been prepared to demonstrate the effect of controlling the light of FP laser due to laser beam from DFB laser. Two PM couplers have been used and they were connected together with the help of PM single mode fiber. DFB laser had to be isolated from light coming from FP laser with fiber isolator. Spectral properties of FP laser were controlled with DFB laser light. If the power from DFB laser had been large enough, light of FP laser has changed its spectral properties. Light form this laser diode that contained several longitudinal modes became single mode and wavelength of FP laser copied the wavelength of DFB laser. The controlled concurrence of modes in FP laser is the basis of such behavior. Spectral properties have been measured with optical spectrometer. Several parameters of this effect were specified - threshold power for particular FP laser modes, power of true single modes in FP laser, range of wavelengths when it was possible to observe this effect.

It has been demonstrated that external influences like temperature,

driving current has can influence strongly the above mentioned parameters. PM devices improved the stability of behavior. The precise tuning of DFB laser has achieved with the temperature changing of DFB laser. The FRL15DCWA 19270 DFB laser module has been used for experiments. The laser diode output is equipped with PM pigtail that can be connected directly to PM coupler. LPS 1550 laser diode has been used as a FP LD. Experiments show that such LD structure can be used as a part of sensitive sensor and optical switch. Exact results will be presented in contribution.

8432-67, Poster Session

Optical injection locking of spatial modes and polarization modes in single-aperture VCSELs and VCSEL arrays emitting at 1.3 µm

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We report the injection locking of specific spatial modes and polarization modes of 1.3µm vertical surface emitting lasers (VCSELs) in single-aperture devices and phase-coupled arrays. The optical injection is realized using a master laser (ML) VCSEL, the beam of which is directed onto the output facet of the slave laser (SL) VCSEL or VCSEL array. We measured the emission spectra of the SL as the ML operating conditions (frequency, power, and injection location) were varied systematically, and present the results on two-dimensional stability maps of power versus detuning of the ML from the injected modes. In comparison with traditional stability maps, a new aspect of characterization is added in these maps by introducing directly in the maps the locking level using a continuous color scale.

In single-aperture devices, the high degree of circular symmetry allows it to support two modes with different polarizations and slightly different frequencies. With injection, we could induce a polarization mode switching and decrease the power of the free running mode by 25 dB, which is a strong indication that injection locking occurs.

In a 1x2 VCSEL array defined by tunnel junction patterning and biased below threshold, the fundamental mode (1x2 mode) and « broad area » mode (1x3 mode) are locked for three different locations of the ML spot (upper and lower array elements and their midpoint). The spatial overlap between ML spot and array mode is shown to be a key factor in injection locking, and locking of the non-lasing 1x3 mode results in suppressed output power of the free running 1x2 mode. These studies are useful for understanding the mode structure of these VCSELs and ways for their discrimination.

8432-68, Poster Session

Volume Bragg grating temperature gradient effect on laser diode array and stack spectra narrowing

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External cavity Volume Bragg Grating (VBG) spectra locked narrow line-width diode laser array and stack is crucial to alkali laser's development. Single bar laser diode array with strip VBG has achieved extreme narrow line-width with high efficiency, and had been successfully applied to Cesium, Rubidium, Potassium vapor laser pumping. However, According to some recent literatures, it is difficult to narrow multi-array laser diode stack down to 0.3nm and may be even broader. It had been reported that this phenomena mostly originated from each bar's slightly direction difference due to packaging process.

This paper explored another cause, hence, thermal gradient issues. Due to low thermal conductivity of PTR glass, even with extreme low absorption rate, temperature gradient must be built to allow deposited heat dissipated effectively. Finite element analysis modeling showed that this kind of gradient may be significant with large area VBG. Experiments were carried on a 64 emitter diode laser array and temperature gradient was intentionally imposed on a strip VBG front of it, spectral output of each emitter was monitored. It was found that each emitter's center wavelength position consistent well with measured temperature distribution and FEA modeling results, hence, the total spectra was notably broadened due to each emitter's center wavelength shift. This gradient effect may be even much significant with brim water cooled large area VBG, and maintaining narrow line-width output may be difficult due to this inherent thermal gradient. Careful cooling scheme should be considered according to this study.

8432-69, Poster Session

850-nm VCSEL with a liquid crystal overlay

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We develop an in-house technology to overlay liquid crystal (LC) on top of a Vertical - Cavity Surface - Emitting Laser (VCSEL) creating a so-called LC-VCSEL. The first step consists of gluing thin glass plates with preliminary deposited on them conducting ITO layer and LC aligning polyimide layer to the both sides of the VCSEL wafer as packaged in a TO-can. The orientation of the LC director is chosen either parallel or perpendicular to the VCSEL light propagation direction. It is also perpendicular to the direction of the applied electrical field, in order to achieve efficient electro-optic tuning of the LC refractive indices. Room temperature LC E7, with positive dielectric anisotropy, is used. To properly orient the glass plates with respect to the polarization direction of the VCSEL (either parallel or perpendicular) the solitary laser polarization resolved light-versus-current and spectral characteristics are measured prior to fixing the glass plates. Next, LC is inserted between the glass plates creating a LC cell in transverse configuration, i.e. the output light from VCSEL propagates in direction perpendicular to the direction at which an electric field is applied to the LC. The degree of LC alignment depends on the thickness of the LC cell and is measured by a polarizing microscope. Finally, optical fiber with attached metal mirror to the fiber facet is inserted into the LC cell facing the VCSEL and therefore, creating a second LC-filled cavity next to the VCSEL one. The length of LC cavity can be precisely tuned by translation and piezoelectric stages. We will present experimental results on threshold, spectral and polarization characteristics of the LC-VCSEL as well as on the impact of externally applied electric field to the LC on these characteristics.

8432-70, Poster Session

Extended synchronization resulting from resonant phase and intensity dynamics in a dual-polarization laser

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Frequency synchronization of a dual-polarization laser beat-note with a radiofrequency signal is experimentally and numerically found without phase locking. This behavior occurs when the laser is subject to a weak frequency-shifted polarization-rotated feedback which excites the relaxation oscillations of the laser. We observe an extended frequency synchronization range beyond the phase locking limit given by Adler's equation. We show that synchronization persists even if the intensities of

the laser modes are pulsed, low frequency modulated, or even chaotic.

The experimental setup consists in a dual-polarization diode-pumped Nd:YAG laser that exhibits relaxation oscillations at frequency f_R = 70 kHz. The frequency difference between the two simultaneously oscillating modes is $\Delta\nu\_0 \approx$ 200 MHz. The two laser modes are optically coupled by the feedback cavity, including a Bragg cell and a quarter-wave plate, that reinjects the x-polarized mode, frequency shifted by 2f_AO, on the y-polarized mode. By increasing the detuning $\Delta\nu\_0$ - 2 f_AO, we then observe different regimes from phase locking to weak intensity modulation, passing through windows of self-pulsing and chaotic oscillations. Of particular physical interest is the fact that frequency locking persists (the relative phase difference remains bounded) if this detuning exceeds Adler's phase locking condition.

Numerical simulations are based on a two-mode rate equation model with coupled population inversion reservoirs. Both intensity and phase dynamics are well reproduced by the simulations. Our model predicts that the two mode synchronization phenomenon occurs for a large domain of the control parameters. We have explored different asymptotic limits of the rate equations. As the effect of the feedback becomes similar to a pure injected signal, we have identified a Hopf bifurcation branch to bounded phase oscillations close to the steady-state phase limit-point. This bifurcation allows extended synchronization beyond this limit-point. Applications of these ideas to VECSELs are under study.

8432-71, Poster Session

Discrete mode laser diodes for FTTH/PON applications up to 10 Gbit/s

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In high volume applications, such as Fibre to the Home (FTTH) networks, component cost is of key importance. The use of uncooled direct modulation transmitter lasers eliminates the need for a thermoelectric cooler (TEC) as well as the associated control electronics allowing the use of lower cost packages such as TO-cans. A challenge is to produce single mode lasers with the requisite performance at low cost. At high ambient temperatures lasers made with AlGaInAs materials show improved performance when compared with those made in conventional material systems such as InGaAsP/InP due to the higher conduction band offset for this material [1, 2]. When AlGaInAs materials are used to fabricate DFBs two or more epitaxial regrowth steps are required [3], but great care is required that unintended oxidation does not compromise material integrity and performance. DFB lasers are relatively complex structures, which increases their manufacturing cost and in addition the regrowth steps for grating formation can deleteriously impact device lifetime if the regrowth process results in oxidation of the aluminium bearing layers. In this paper we describe Discrete Mode Laser Diodes (DMLDs) which present and economic approach in the AlGaInAs material system with a focus on high volume manufacturability. DMLDs are simple in structure comprising a regrowth-free ridge waveguide Fabry-Pérot laser. Single wavelength operation in DMLDs is achieved by introducing index perturbations in the form of etched features positioned at a small number of sites distributed along the ridge waveguide [4].

Static and dynamic characteristics are presented for DMLDs operating at 1310 nm and 1550 nm. Under direct modulation at 10 Gbit/s open eye diagrams were measured for lasers operating at both wavelengths. The Bit Error Ratio (BER) was measured back to back and after transmission through Single Mode Fibre (SMF). At 1310 nm power penalties, at a BER of 1E-9, of 0.25 and 0.3 dB were measured after transmission through 10 and 22 km of SMF respectively; no error floors were observed. At 1550 nm after transmission through 10 km of SMF a power penalty of ~ 0.8 dB was measured, with no error floor, this increased to 5.3 dB after transmission through 20 km and an error floor was observed due to dispersion effects. Larger transmission distances can be achieved at 1550 nm using dispersion compensation [5]. Dispersion compensation was used to increase the transmission distance to 60 km of single mode fibre where a power penalty of 3.6 dB was measured. Pre-compensation of dispersion was achieved by placing the dispersion compensation module, with -681 ps/nm dispersion, after the laser. Using a signal pre-compensation module a maximum power penalty of 3.6 dB was measured after transmission through path lengths in the range 0 to 60 km.

References:

[1] C.E. Zah, et al., IEEE J. Quantum Electron., 1994, 30, pp. 511-523

[2] J. Piprek, etal, IEEE J. Quantum Electron., 2002, 38, (9), pp. 1253-1259

[3] R. Phelan, et al., IEE Electronics Letters, vol. 45, no 1, pp43-45, (2009).

[4] C. Herbert, et al., IET Optoelectronics , vol.3, no.1, pp.1-17, February 2009

[5] X. Cheng, et al., ECOC2008, September 2008, Brussels, Belgium, Paper: P.6.02.

8432-73, Poster Session

Red AlGaInP-VECSEL emitting at around 665 nm: strain compensation and performance comparison of different epitaxial designs

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With usage of external cavities and optical excitation, vertical external cavity surface-emitting lasers (VECSELs) arise with high continuous-wave output power and near diffraction-limited beam quality with a TEM_{00} Gaussian beam profile. These impressive features of the VECSEL made it to an important category of power-scalable semiconductor lasers in a wide range of applications like biophotonics, television and projectors or spectroscopy.

The active region consists of a multi-quantum-well structure with compressively-strained GaInP quantum wells (QWs). These are placed in packages separated by $(Al_{0.55}Ga_{0.45})_{0.51}In_{0.49}P$ cladding layers in a resonant periodic gain design. The QWs itself are embedded in $(Al_{0.33}Ga_{0.67})_{0.51}In_{0.49}P$ barrier layers. The active region is fabricated on a 55 $\lambda/4$ pairs $Al_{0.50}Ga_{0.50}As$/AlAs distributed Bragg reflector to form the active mirror. Bonding an intra-cavity heatspreader diamond plate on top of the VECSEL chip enables continuous-wave operation.

Several VECSEL designs were fabricated in our metal-organic vapour-phase epitaxy with different QW distributions in the active mirror. One design includes 4 QWs in 5 packages whereas the other contains 10 QW pairs to have a larger absorption length. Laser parameters like output power, differential efficiency and threshold pump power of the different chip designs are examined. By using the 10x2 QW distribution in the chip, we could improve the absorption efficiency by nearly 40 % and output power by 25 %. Furthermore, fabrication of a VECSEL with tensile strained barriers leads to improved laser characteristics. With this strain compensation technique, the output power could be increased over 30 % compared to our conventional structure.

8432-74, Poster Session

Experimental demonstration of spatial rocking in a low Fresnel number nondegenerate optical oscillator with injected signal

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Free running lasers are phase invariant systems, but when a monochromatic signal is externally injected into the laser cavity its frequency and phase can lock to that of the injection. The laser field phase is then locked to a single value. For some purposes it would be important that the laser field phase locks not to a single value but to two different values (bistable phase locking). Phase bistability is different from conventional optical bistability, where the field intensity (not the phase) can take two different values.

A way to change phase-invariant systems into phase-bistable ones was proposed by some of us [1] that consists in injecting a resonant signal into the cavity, whose amplitude's sign alternates periodically in time. Such forcing technique, called "rocking" because of the effect it has on the potential describing a laser (in a mechanical analogy) [1], has been shown to lead to phase bistability and to its associated patterns in a photorefractive oscillator [2] and other systems.

In [3] some of us proposed an alternative mechanism for inducing the bistable phase locking in a low Fresnel number laser, inspired in the rocking technique. In consists in the transverse spatial modulation of a nearly resonant, monochromatic injected signal. The basic setup is a laser with spherical mirrors oscillating at a TEM00 mode, and the injected signal has a TEM10 cavity mode shape, which shows two opposite phase values in adjacent spatial domains. Then, the TEM00 mode will lock to some phase value but, as two opposite phases are injected simultaneously, phase bistability is expected, and observed under appropriate conditions [3].

Here we experimentally demonstrate the above mechanism in a laser-like system, a nondegenerate BaTiO3 photorefractive oscillator with spherical mirrors [4]. Observations are supported by an analytical study of the model.

References

[1] G. J. de Valcárcel and K. Staliunas. "Excitation of phase patterns and spatial solitons via two-frequency forcing of a 1:1 resonance," Phys. Rev. E. 67, 026604 (2003).

[2] A. Esteban-Martín et al., "Bistable phase locking of a nonlinear optical cavity via rocking: transmuting vortices into phase patterns," Phys. Rev. Lett. 97, 093903 (2006).

[3] K. Staliunas, G. J. de Valcárcel, and E. Roldán, "Bistable phase locking in a laser with injected signal", Phys. Rev. A 80, 025801 (2009).

[4] K.Staliunas, M.F.H. Torroja, G. Sleakys, C.O.Weiss, and L.Dambly, Phys.Rev.A51, 4140 (1995)

8432-75, Poster Session

Optical noise and alpha-factor in the broadband emission of quantum dot laser

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Broadband (up tp 70 nm wide) stimulated emission of quantum dot (QD) laser can be potentially used in a variety of applications such as DWDM transmitters. The noise and stability of lasing spectrum are key issues in practical implementation of QD laser advantages. Therefore intensity noise and phase noise properties of the QD lasers are currently of great interest. In the broadband emission intensity noise and phase noise are closely connected as both are related to interaction between lasing modes. So in this paper intensity optical noise and phase noise related to alpha-factor in quantum dot lasers have been studied theoretically. We also studied the alpha-factor in connection with stability to parasitical optical feedback.

The conventional Langevin approach was applied to study intensity noise properties of the quantum dot laser. The diffusion coefficients of Langevin forces were calculated in the model of four-level quantum dot. Pauli blocking was taken into account. Inhomogeneous broadening and gain compression that play major role in the formation of a lasing spectrum of the quantum dot laser and their impact on laser noise were discussed in details in our examination. We also accurately introduced interplay between homogeneous and inhomogeneous broadening in our approach. In the quasiclassical description in the absence of mode interference we found no qualitative difference in behavior of both quantum dot and quantum well lasers. Mode partition noise in the case of multi-mode broadband lasing is the main source of output noise. It contradicts the experiments on multi-mode comb lasers where mode partition noise in quantum dot laser was demonstrated to be suppressed. The origin of this contradiction is discussed in terms of complicated charge carrier dynamics in quantum dot ensemble together with interference between modes.

The charge carrier dynamics also plays major role in the value of alpha-factor in the quantum dot laser operating far above the threshold. We demonstrated that the key points are redistribution of carriers between quantum dots with different energies of optical transitions as well as between ground and excited states in the quantum dots. Filling of the excited states in the quantum dots may seriously increase alpha-factor to the values higher than unity. We also demonstrated that due to slow carrier relaxation in quantum dot ensemble alpha-factor can be frequency dependent. Small signal analyses of the Fokker-Planck type equation for carriers in the inhomogeneous QD ensemble was carried out. For the processes fast enough alpha-factor can be order of magnitude less than its static value. This fact is important when experimental data obtained by different techniques are compared and also when laser properties such as jitter are discussed.

8432-76, Poster Session

Improving beam quality in broad area semiconductor amplifiers

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Broad area semiconductor amplifiers are important devices for technological applications. Their main advantages are an efficient access of the pump to amplifying media and their possible high and wide output, very suitable for telecommunication applications. On the other hand, their main disadvantage is the bad spatial quality of the beam due to the many spatial modes involved in their emitted light. In fact, not only spatial noise appear, but the broad area allows many transverse modes to oscillate simultaneously leading to spatio-temporal dynamics. All these effects introduce instabilities and filamentation decreasing drastically the emitted output beam quality [1].

We study spatial modulations amplifiers in both the propagation and transverse directions and the influence on the spatial quality of the amplified beam.

We introduce a sinusoidal 2D spatial modulation in such semiconductor through the injection current of the active medium and we choose a simple configuration dealing with a rhombic geometry.

The model considers an entering beam propagating paraxially through one of the diagonal directions of the structure.

The spatial modulations of the refractive index introduce strong modifications on spatial dispersion relations, allowing the management of diffraction [2]. Moreover, the introduction of Gain/Loss Modulations (GLM) in the materials introduce directional gain and the possibility to manage the beam diffusion allowing interesting effects to improve the quality of output beams like space filtering and focalization behind the modulated material [3]. In semiconductor materials and due to the so called enhancement factor, corresponding to the refraction index dependence on inversion in the semiconductor material, both modulations appear together.

The improvement of output beam profiles is simulated by a simple model commonly used for broad area semiconductor heterostructures with or without current injection. The model considers the interaction of the slowly varying amplitude of field E and carrier density N [4].

[1] O.Hess, T.Khun, Prop. Quant. Eectr. 20, 85 (1996). O.Hess, S.W. Koch, J.V. Moloney, IEEE Journal of Quantum Electronics, 31, 35 (1995)

[2] P. T. Rakich et al., Nat. Mater. 5, 93 (2006), T. Pertsch, T. Zentgraf, U. Peschel, A. Brauer, and F. Lederer, Phys. Rev. Lett. 88, 093901 (2002), K. Staliunas and R. Herrero, Phys. Rev. E 73, 016601 (2006). Yu. Loiko, e.a, Opt.Comm., 269, 128 (2007)

[3] K.Staliunas, R.Herrero, R.Vilaseca, Phys. Rrev. A 80, 013821 (2009),

M.Botey, R.Herrero, K.Staliunas, Phys. Rev. A 82, 013828 (2010).

[4] M.Brambilla, L.A.Lugiato, F.Prati, L.Spinelli, W.J.Firth, Phys.Rev. Lett., 79, 2042 (1997)

8432-77, Poster Session

Interplay between phase space filling and band non-parabolicity in quantum-cascade lasers

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Employing density-matrix formalism we investigate joint influence of the phase-space flling effect, many-body effects and band non-parbolicity on intersubband optical gain in quantum-cascade lasers operating in stationary regime above threshold. Obtained results evidence that in quantum-cascade sctuctures interplay between band non-parabolicity and phase space filling causes appearing of the gain without global population inversion that strongly depends on the electron density in the active region. Results of theoretical modeling for the considered structure show that spectral shift caused by the exchange interactions is compensated by the Fermi-edge singularity and depolarization shifts for wide ranges of electron densities. In considered structure operating above the threshold, peak gain and many-body effects do not depend on the total electron density in the active region being only dependent on the inversion of populations.

8432-78, Poster Session

Development of epitaxially regrown vertical-cavity surface-emitting lasers

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The transistor laser is a generically new device type that has attracted significant interest during the past few years. Such devices have a number of interesting features with possible general implications for optical communication and optoelectronic integration, including the potential for substantially increased modulation bandwidth due to the altered charge dynamics in the base (cavity) region [1]. Here, we report on the design and fabrication of a vertical-cavity surface-emitting transistor-laser (T-VCSEL) based on epitaxial regrowth and intra-cavity carrier injection. The design employs three InGaAs/GaAs quantum wells (QWs), an undoped bottom semiconductor AlGaAs/GaAs distributed Bragg reflector (DBR) and a dielectric amorphous Si/SiO2 top (out-coupling) DBR, and is based on our previous development of GaAs-based VCSELs for the 1.3-µm regime [2]. Numerical simulations are implemented using a commercial software package, PICS3D [3], and are calibrated against measurements on conventional VCSELs. The calculated steady-state operation of a T-VCSEL is used as input for an analytical model to predict the small-signal high-speed modulation performance for different device configurations [4,5]. On the fabrication side, a particular challenge relates to the high base doping density required for the high-frequency operation of the built-in heterojunctions base transistor. This doping is of particular importance for the improved laser modulation bandwidth but may also cause serious problems related to excessive carrier recombination, optical absorption and QW degradation. We have here used a variety of experimental techniques to investigate this in detail on both n-doped (Si) and p-doped (Zn or C) device structures to provide important guidelines for the active region design.

[1] N. Holonyak and M. Feng, “The transistor laser”, IEEE Spectrum 43 (2), 50 (2006)

[2] R. Marcks von Würtemberg et al., “Performance optimization of epitaxially regrown 1.3-µm VCSEL”, IET Optoelectronics 3 (2), 112 (2009)

[3] www.crosslight.com

[4] B. Faraji et al, “Analytical modeling of the transistor laser”, IEEE J. Sel. Top. Quantum Electron. 15 (3), 594 (2009)

[5] W. Shi et al, “Design and modeling of a transistor vertical-cavity surface-emitting laser”, Optical and Quantum Electronics, Vol. 42, Iss. 11-13, pp. 659-666 (2011)

8432-79, Poster Session

Carrier escape from ground state and non-zero resonance frequency at low bias powers for semiconductor quantum-dot lasers

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The three-dimensional confinement of electrons and holes in a semiconductor quantum dot (QD) profoundly changes its density of states compared to a bulk semiconductor or thin-film quantum well (QW). QD lasers are expected to exhibit many useful properties such as low threshold current, temperature and feedback insensitivity, chirpless behavior, and low linewidth enhancement factor [1]. The aim of this paper is to theoretically investigate the microwave properties of InAs/InP(311B) QD lasers [2]. The model is based on a set of four rate differential equations [3]. Carriers are supposed to be injected directly from the contacts into the wetting layer (WL) levels, so the barrier dynamics is not taken into account in the model. Then, carriers are captured into the exited state (ES) or directly into the ground state (GS) within the same time whereas they can also relax from the (ES) to the (GS). Modelling is assumed that at low injection rate, the relaxation is phonon-assisted while the Auger effect dominates when the injection gets larger [4]. Based on a small-signal analysis, a new expression of the modulation transfer function is derived for QD lasers [5]. Analytical calculations point out that the carrier escape from (GS) to (ES) induces a non-zero resonance frequency at low bias powers. This frequency offset is larger than the one due to spontaneous emission only in QW lasers [6]. Similar behaviour is also observed when plotting the calculated damping factor as a function of the squared resonance frequency. Such a deviation from linearity at low resonance frequencies is also attributed to the carrier escape from (GS) to (ES), which leads to a larger damping factor offset as compared to conventional QW lasers [6]. These results are of prime importance for a better understanding of the carrier dynamics in QD lasers as well as for further optimization of low cost sources for optical telecommunications.

References

[1] M. T Crowley et al., Semiconductors and Semimetals, vol. 86, (2012).

[2] A. Martinez et al., Appl. Phys. Lett., vol. 93, pp. 021101, (2008).

[3] K. Veselinov et al., IEEE J. Quantum Electron., vol. 43, pp. 810-816, (2007).

[4] F. Grillot et al., IEEE J. Quantum Electron., vol. 45, pp. 872-878, (2009).

[5] L.A. Coldren et S.W. Corzine, Wiley, New York, (1995)

[6] C. B. Su et al., IEEE J. Quantum Electron., vol. 28, pp. 118-127, (1992).

8432-81, Poster Session

Self-mixing in VCSELs for multi parametric sensing applications: theory and experiment

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The self-mixing interferometry in conventional diode lasers has been largely exploited for the realization of compact, contactless, sensors for real time and high precision measurements of e.g absolute distance, vibration, rotations. In order to simultaneously measure target displacements with more than one degree of freedom, customized multi sources configurations are currently used.

We developed a general model for mid-area VCSELs with multi transverse mode field profile whose dynamics is sensitive to simultaneous target translation and rotation. The model considers an optical feedback provided by an external mirror with spatially modulated reflectivity. When the field profile can be described by a limited set of Gauss-Laguerre modes, our numerical simulations show the existence of dynamical regimes where transverse mode-locking occurs (with a peculiar spatial profile of the emitted and feedback fields). The developed model is generalized to encompass multiple external reflections, non self-imaging configuration, field polarizations and residual birefringence and dichroism.

The experimental results have been obtained with a small-size (about 10μm) multi transverse mode commercial VCSEL in a self-imaging external cavity subject to polarization controlled optical feedback from an external mirror. Both the fundamental and the first-order transverse modes allow for polarization rotation sensing schemes, while preserving, at the same time, independent signatures of the longitudinal displacement (the typical saw-tooth fringes observed in the moderate feedback regime). In particular, for a proper choice of the feedback level, mode switching between the TEM01 and TEM10, along each polarization component, have also been observed upon rotation of the feedback polarization. These preliminary experimental results are in good agreement with the theoretical predictions and allow us to propose an operational scheme for a sensor that can simultaneously measure target translations along the optical axis and target rotations in the orthogonal plane using a single semiconductor laser.

8432-44, Session 10

Gain model for Ge laser

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This paper reports on a connection between n-doping and energy separation between conduction energy minima because of many-body effects. Gain spectra for bulk Ge were computed using semiclassical laser theory with many-body effects treated at the level of the screened Hartree-Fock approximation. The spectra show significant modification of the free-carrier results from many-body effects leading to appreciable lowering of L-band energies at high doping density. Calculated difference in band edge energy between Gamma and L conduction bands versus doping density are presented for different values of injected carrier density and tensile strain. Results are presented showing the injected current density necessary to obtain a desired peak material gain. Contributions from spontaneous emission, defect carrier loss and Auger recombination are taken into account. The results are summarized in the form of a plot of injected current density necessary to achieve a desired peak material gain versus doping density. Different curves for different tensile strain will be shown.

8432-45, Session 10

Deterministic and stochastic dynamics of linear polarizations emitted by single-mode VCSELs subject to orthogonal optical injection

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Optical injection can induce a rich variety of nonlinear dynamics in the light emitted by a semiconductor laser. Nonlinear dynamics of optically injected long-wavelength Vertical-Cavity Surface-Emitting Lasers (VCSELs) has been recently studied. Most of the studies consider linearly polarized light from a tunable laser that is injected orthogonally to the linear polarization of a free-running VCSEL, the so-called orthogonal optical injection [1].

We perform an experimental and a theoretical analysis of the polarization-resolved nonlinear dynamics of a 1550 nm wavelength single-mode VCSEL when subject to orthogonal optical injection. Special attention is paid to the case of negative frequency detuning, for which irregular dynamics has been observed experimentally [2]. Our theoretical analysis of the deterministic system is performed by using the numerical simulations of the Spin Flip Model. Complex dynamics including period 2, 3, 4 and irregular dynamics are observed in both linear polarizations. Deterministic dynamics with appreciable values of the standard deviation of the period of the signal is also found. The effect of spontaneous emission noise on the dynamics of the system is studied by including the corresponding stochastic terms in the equations of the model. We analyze the dependence of the average and standard deviation of the interpulse time on the injected power. The interpulse time is defined as the time between two consecutive peaks of the temporal series corresponding to the total power. We find that spontaneous emission noise i) can break the periodic character of the deterministic time traces, and ii) usually increases the standard deviation of the interpulse time.

[1] K. Panajotov, I. Gatare, A. Valle, H. Thienpont, M. Sciamanna, IEEE J. Quantum Electron, vol. 45, no. 11, pp. 1473-1481, 2009.

[2] A. Quirce, P. Pérez, A. Valle, L. Pesquera, Journal of the Optical Society of America B, vol. 28, no.11, pp. 2765-2776, 2011.

8432-46, Session 10

Polarization switching of transverse modes in VCSELs subject to two-frequency orthogonal optical injection

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Optical injection is a technique that improves the performance of vertical-cavity surface-emitting lasers (VCSELs) without modifying their design. In the orthogonal optical injection configuration the polarization of the injected signal is perpendicular to that of the VCSEL that receives the injection. Experimental and theoretical work has shown that under single-frequency orthogonal optical injection a high-order transverse mode can appear locked to the external injection with a polarization direction given by that of the injected signal [1]. Recent experimental work has demonstrated single-mode [2] and multimode [3] VCSEL-by-VCSEL optical injection locking. These studies have interest for obtaining integrated low-cost high-speed communication modules [2].

In this work we study in a theoretical way the polarization and transverse mode properties of a multimode VCSEL when it is subject to two-frequency orthogonal optical injection. We consider that the injected signal comes from another multimode VCSEL. The dynamics of the two linear polarizations of two transverse modes of the VCSEL is found using the model of [1] extended to consider dual-beam injection. We consider the case in which the injected power is kept constant and the frequency detuning between the external signal and the injected VCSEL is changed. We observe polarization switching in each transverse mode for a certain range of the frequency detuning, in agreement with results reported in [3]. Frequency locking between the two orthogonally polarized transverse modes is observed for large enough values of the injected power. The RF spectrum consists on a single peak that appears at the frequency corresponding to the transverse mode separation. Both transverse modes oscillate in phase at that frequency with large modulation amplitudes. This dynamic state of period one oscillation can find applications in photonic microwave generation [4].

[1] A. Valle, I. Gatare, K. Panajotov, M. Sciamanna, IEEE J. Quantum Electron., vol. 43, no. 4, 322-333, 2007.

[2] A. Hayat, A. Bacou, A. Rissons, J. C. Mollier, V. Iakovlev, A. Sirbu, E. Kapon, IEEE Trans. Microw. Theory Tech. Vol. 57, no 7, 1850-1858, 2009.

[3] H. Lin, D. W. Pierce, A. J. Basnet, A. Quirce, Y. Zhang, A. Valle, Opt. Exp., vol. 19, no. 23, 22437-22442, 2011.

[4] X. Q. Qi, J. M. Liu, IEEE J. Selec. Top. in Quantum Electron, vol. 17, no. 5, 1198-1211, 2011.

8432-47, Session 10

Delay induces motion of multipeak localized structures in VCSEL devices

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Localized structures often called cavity solitons are nonlinear bright or dark pulses in spatially extended systems. They have been observed in the transverse section of coherently driven nonlinear optical cavities. They attract a growing interest due to their potential application for all optical control of light (see recent overview on this issue^{1}). When they are well separated from each other, localized peaks are independent or randomly distributed in the transverse plane. However, when they are close one to another they start to interact via their oscillating, exponentially decaying tails. This interaction leads to clustering phenomenon.

This behavior is relatively well understood. So far however, the inclusion of delay feedback in the dynamics of spatially extended systems is relatively a new area of research^{2,3}.

In this communication we consider a broad area vertical cavity surface-emitting laser subject to injection and to time-delayed feedback. We focus on a nascent optical bistability regime. We show that in this regime the space-time dynamics of this device is described by a delayed generalized Swift-Hohenberg equation. More importantly, we show that the delay feedback induces a spontaneous motion of clusters that can be formed either by dark or bright peaks. We calculate the velocity of localized peaks and make a comparison between numerical and theoretical results.

Bibliography:

1: Barbay, S., Kuszelewicz, R., and Tredicce, J. R.,'Cavity solitons in vcsel devices', Advances in Optical Technologies 2011 (2011).

2: Tlidi, M., Vladimirov, A. G., Pieroux, D., and Turaev, D., 'Spontaneous motion of cavity solitons induced by a delayed feedback', Phys. Rev. Lett.103, 103904 (Sep 2009).

3: Panajotov, K. and Tlidi, M., 'Spontaneous motion of cavity solitons in vertical-cavity lasers subject to optical injection and to delayed feedback', Eur. Phys. J. D 59(1), 67-72 (2010).

8432-48, Session 10

Dynamics accompanying polarization switching in vertical-cavity surface-emitting lasers

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Vertical-cavity surface-emitting lasers (VCSELs) are known to exhibit many advantages over edge-emitting lasers but still suffer from severe polarization instabilities. Experiments on quantum well [1] and recently quantum dot [2] VCSELs have shown that the increase of injection current may lead to a transition from a linearly polarized light emission at threshold to a region of nonlinear dynamics (self-pulsing) accompanying polarization switching between either two orthogonal linearly polarized states [1] or non-orthogonal elliptically polarized states [2]. The dynamics occurs on a nanosecond time-scale and relates either to the birefringence induced frequency splitting [1] or to the relaxation oscillation frequency [2]. The bifurcation mechanism behind the emergence of self-pulsations and what determines the self-pulsing frequency need further clarifications.

In this contribution, we bring new light into the bifurcation mechanisms explaining the occurrence of deterministic self-pulsing accompanying polarization switching. Our work is based on the spin-flip model (SFM) [3] and makes use of advanced numerical continuation techniques for dynamical analysis. We demonstrate theoretically that depending on the laser parameters, different polarization switching scenarios may be observed with self-pulsing dynamics at a dominant time-scale related to either linear cavity birefringence or relaxation oscillation, and with additional period doubling or quasiperiodicity. Our work therefore not only reconciles previous experiments with different conclusions on dynamical states, but also provides an improved understanding of the bifurcations underlying the commonly used spin flip model for VCSEL [4]- hence motivating new in depth experiments of polarization dynamics at nanosecond time scale.

[1] Sondermann and al., Opt. Commun., vol. 235, pp. 421 (2004).

[2] Olejniczak and al., Optics Express, vol. 19, pp. 2476 (2011).

[3] Martin-Regalado and al., IEEE J. Quantum Electron., vol. 33, pp. 765 (1997).

[4] Prati and al., Phys. Rev. A, vol. 69, pp. 033810 (2004).

8432-50, Session 11

True photonic band-gap in vertical-cavity surface-emitting lasers

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Application of photonic crystals (PhCs) in vertical-cavity surface-emitting lasers (VCSELs) has attracted a lot of interest as a way to improve their optical properties [1-3]. The potential advantages offered by such PhC-VCSELs are the enhanced single-mode operation, polarization control, and high speed of modulation. However, the common property of present PhC-VCSELs is the mechanism of light confinement, namely an index-guiding inside the defect area of higher refractive index, which is different from the true band-gap confinement of short-period lattice surface emitting lasers [4]. This is confirmed by the fact that simplified numerical models that use only the concept of local effective index yield a good agreement with the experiments [5]. Hence, the question arises: is it possible to create the true photonic-crystal VCSEL, i. e. the one with the electromagnetic field confined through Bragg reflection of a 3D band-gap rather than total internal reflection? In the talk we demonstrate that full PBG light confinement can actually be realized for the TE-like polarization, which in fact is the only significant one in VCSELs due to the quantum well properties. Such PhC-VCSELs would in fact be true PBG-VCSELs. For this purpose we propose a modified VCSEL distributed Bragg reflector (DBR) consisting of a periodic stack of pairs of high-contrast high and low refractive index layers with triangular two-dimensional lattice of air holes. Such a structure can be treated as a 3D PhC and we show that it possesses a photonic band-gap for TE-modes [6]. In case of the k-vector not laying in the KM plane, where the modes are characterized as partially TE- or TM- by considering the mode parity, there is still a well-pronounced band-gap in the TE-like (even) modes and hence, PBG confinement of the light is possible in any PhC-VCSELs utilizing proposed DBRs.

We also consider a PhC cavity created by a low-index defect surrounded by the proposed DBRs. We calculate its resonant modes with our efficient plane-wave admittance-method [7]. Due to the truly PBG light confinement, the Q-factor of such cavity reaches Q = 43 000, which is about three times higher than the one of the state-of-the-art oxide-confined VCSELs [8] and more than ten times higher than the one of typical PhC-VCSELs [9].

References:

[1] D. S. Song, S. H. Kim, H.G. Park, C.K.Kim, Y.H. Lee, Appl. Phys. Lett. 80, 3901(2002).

[2] A. J. Danner, T. S. Kim, and K. D. Choquette, Electron. Lett. 41, 325(2005).

[3] T. Czyszanowski, M. Dems, K. Panajotov, Opt. Express 15, 560(2007).

[4] S. Noda, M. Yokoyama, M. Imada A. Chutinan,M. Mochizuki, Science 293, 1123(2004).

[5] A. J. Danner, J. J. Raftery, P. O. , and K. D. Choquette, Appl. Phys. Lett. 88, 091114(2006).

[6] K. Panajotov, M. Dems, Opt. Lett. 35, 829(2010).

[7] M. Dems, R. Kotynski, K. Panajotov, Opt. Express 13, 3196(2005).

[8] P. Leisher, J. Raftery, Jr., A. Kasten, K. Choquettea, J. Vac. Sci. Technol. B 24, 104(2006).

[9] M. Dems, T. Czyszanowski, K. Panajotov, Opt. Quant. Electron., 39 419(2007).

8432-51, Session 11

Simulation of 1550-nm diamond VECSEL with high contrast grating

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Vertical external cavity surface emitting lasers (VECSEL) are attractive light sources combining high output power up to several Watts and high beam quality with compact dimensions. For efficient operation the most crucial is the heat management. Usually one, top diamond heat spreader is employed to decrese the thermal resistance of device. It redistributes the heat flow to the lateral regions of VECSEL so the heat can be transported down to the copper heat sink more efficiently. We present here further improvement of the heat management by eliminating the bottom DBR from the heat flow path and substituting it for diamond with high contrast grating (HCG). Hence the active region, which consists of 5 pairs of AlGaInAs quaternary alloy quantum wells, is sandwiched by diamond heat spreading layers.

To rigorously simulate the physical phenomena taking place within the device we used multi-physical model, which comprises three-dimensional models of optical (Plane Wave Admittance Method) and thermal phenomena (Finite Element Method). The structure of Si HCG deposited on diamond provides broad wavelength range in which reflectivity of emitted beam is close to 100% for perpendicular mode polarization with respect to the direction of the HCG trenches. The HCG assures less than 20% reflection and near zero absorption of pumping light, hence it allows for on-axis bottom pumping scheme and integration of the VECSEL with the pumping laser. According to simulations 500 mm of thickness of top diamond heat spreader is enough to provide effective heat dissipation mechanism. Replacement of the bottom DBR with the diamond heat spreader will provide additional reduction of thermal impedance of about 10%. The minimum of thermal impedance is achieved for about 460 mm thick bottom diamond heat spreader.

The full optical performance of such structure will be presented including threshold and emitting power as a function of pumping power. Optimization of pumping beam diameter and both diamonds thickness for achieving the highest output power will be shown.

8432-52, Session 11

Semiconductor ring lasers as optical neurons

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Semiconductor Ring Lasers (SRLs) are a modern class of semiconductor lasers whose active cavity is characterized by a circular geometry. This enables the laser to support two counterpropagating modes, referred to as the clockwise (CW) and the counterclockwise (CCW) mode. Semiconductor ring lasers have been shown to have a regime of operation in which they are excitable, when the linear coupling between the counterpropagating modes is asymmetric. This can be achieved by increasing the reflection of, for example, the CW mode into the CCW mode. This will stabilize lasing in the CCW mode. In the excitable regime, the SRL will fire optical pulses (spikes) in the CW mode as a response to noise perturbations. In this contribution we experimentally and theoretically characterize these spikes. Our experiments reveal a statistical distribution of the characteristics of the optical pulses that is not observed in regular excitable systems. In particular, an inverse correlation exists between the pulse amplitude and duration. Numerical simulations and an interpretation in an asymptotic phase space confirm and explain these experimentally observed pulse characteristics. We will also theoretically consider asymmetric SRLs coupled through a single bus waveguide. This is a first step towards an integrated optical neural network using semiconductor ring lasers as building blocks. We will show that for weak coupling, excitatory excursions still persist due to the similar phase space structure. Moreover, the coupled SRLs can excite pulses in each other and can thus function as communicating neurons. This type of neural network can be fully integrated on chip and does not suffer from the drawback of needing extra-cavity measures, such as optical injection or saturable absorbers.

8432-80, Session 11

High performance identical layer InGaAlAs-MQW 1300nm electroabsorption-modulated DFB-lasers for 4x25Gbit/s

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We have developed electroabsorption modulated ridgewaveguide-based DFB Lasers for 4x25Gbit/s that comply with the IEEE 100GBASE-ER4 Standard for 100Gbit-Ethernet. An identical InGaAlAs MQW layer stack is used in the DFB and the EAM section. Devices from a single wafer show excellent 25Gbit/s modulation performance at all four wavelengths with dynamic extinction ratios exceeding 9dB. All devices have fiber-coupled output powers over +2dBm and are operated semi-cooled at 45°C.

8432-53, Session 12

Many-body effects and self-contained phase dynamics in an optically injected quantum-dot laser

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Quantum-dot (QD) lasers exhibit unique properties when subjected to optical injection, showing lower sensitivity and less complex dynamics when compared to conventional quantum well (QW) lasers. These features can be explained by a lower phase-amplitude coupling and a higher damping of relaxation oscillations in QD laser devices.

In this work, we investigate the reaction of a QD laser to external optical injection. We model the QD laser device using a semi-classical approach based on the semiconductor-Bloch equations, describing the material-light interaction in a quantum-mechanical framework and the electric field dynamics classically, using Maxwell's equations. We consider carrier-carrier and carrier-phonon scattering between bulk and QW states as well as between QW and QD states within the relaxation rate approximation. All effective scattering rates are determined using microscopic calculations. The QW-QD rates are found to be particularly sensitive to carrier density. The QD optical transition is modeled with a finite spectral width, accounting for inhomogeneous broadening due to QD imperfections. Furthermore, many-body Coulomb interactions, leading to renormalizations of the single-particle energies, are taken into account assuming the screened Hartree-Fock approximation.

Most models implement the phase dynamics of the electric field inside the laser cavity by assuming a constant $alpha$-factor throughout the calculation. Our model accounts for the effects of $alpha$ via a more rigorous treatment of light-semiconductor interaction. The model allows extraction of a value for the $alpha$-factor from the intrinsic phase dynamics of the system. The extracted $alpha$-factor is not a constant, but rather changes dynamically throughout the simulations. Furthermore, the dynamical shift of the band-gap energy due to the Coulomb interactions gives rise to modifications in the locking behavior of the laser, that can not be explained with the simpler free-carrier models.

8432-54, Session 12

Impact of band structure on locking dynamics of quantum dot laser under optical injection

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We study the influence of band structure and of pump current on the locking dynamics of a semiconductor quantum dot (QD) laser under optical injection.

The dynamics of a QD laser is crucially affected by the damping rate of its turn-on relaxation oscillations, which in turn is determined by the carrier lifetimes in the QDs.

We derive the carrier lifetimes by microscopical calculations of the Coulomb interaction between the discrete QD levels and the surrounding quantum well acting as a carrier reservoir. This yields non-constant and unequal carrier lifetimes for electrons and holes in the QDs, which are nonlinear functions of the reservoir carrier densities.

By varying the energy spacing between the quantum well and the QD levels, we can model QD devices with different sizes of the QDs, i.e. with different band structures. Further our model allows to study the dynamics of the laser in dependence of the pump current, which also changes the carrier lifetimes and thus the damping of the relaxation oscillations.

The locking behavior as well as more complex dynamics close to the boundaries and outside of the locking region are studied by direct numerical integration and by path continuation techniques. The dynamics is investigated in terms of injection strength and frequency detuning of the injecting laser.

A stronger damping of the turn-on relaxation oscillations leads to smaller regions of complex dynamics and enlarges the range of stable frequency-locked continuous wave operation.

Tuning the energy spacings, i.e. the band structure, we find an optimal value of the carrier lifetimes that maximizes the range of stable operation.

8432-55, Session 12

Simultaneous multi-state stimulated emission in quantum dot lasers: experiment and analytical approach

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Efficient semiconductor lasers having a broad emission spectra, corresponding to the transparency windows of standard optical fiber and waveguide, are required for a waste range of practical problems: from optical tomography to ultrafast information transfer. It turns out that emission spectra width of InGaAs/InAs QD lasers overlap frequency O-band even at room temperatures and low injection. Moreover, the usage of these multi-frequency laser diodes seems to be an alternative to currently used DFB-lasers (distributed feedback lasers) due to their cheapness and simplicity of fabrication.

At low injection, laser emission is generated by ground state optical transition of QD array. With output power growth population of electron and hole excited levels increases. This leads to an increase of the population inversion of the excited state optical transition and onset of lasing through the QD excited state. We have experimentally found some new features of the simultaneous ground and excited state lasing. Initially, excited state lasing comes from quantum dots that were not involved into lasing through the ground state. Under higher injection lasing through the QD ground states becomes suppressed while most of the QDs are lasing through the excited state. This experimental fact contradicts to the previous understanding that predicts saturation of the power emitted from the QD ground states. Neither analytical theory nor qualitative understanding of interplay of double-state lasing and inhomogeneous broadening has been presented by now.

We have developed an analytical approach that includes consideration of both ground (GS) and excited (ES) electron and hole states, inhomogeneous broadening, gain compression, independent electron/hole captures and technologically induced imperfections. It was also assumed that the energies of hole levels are close due to significant hole effective mass.

At low injections, when laser emission takes place through only the ground states of QDs, we have found analytical expressions for lasing spectra form and width and revealed that they depend only on two dimensionless parameters: inhomogeneous broadening to temperature ratio and losses normalized on maximum gain. It was also shown that the usage of several QD layers with intentionally varied energies of optical transitions leads to enhancement of the laser spectrum full width. Good agreement between theory and experiment has been demonstrated.

Simultaneous lasing through ground and excited QD states, which takes place under high injection, has been also studied in details. We have revealed that the large difference in electron and hole capture rates leads to depletion of hole levels with lasing power growth. This effects strongly on lasing properties, e.g. holes depletion is responsible for damping of GS lasing at high output power observed in the experiments.

8433-01, Session 1

High-power high repetition rate picosecond optical parametric oscillator pumped by frequency doubled all-fibre Yb-doped MOPA

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A growing demand for tunable femto- or picosecond pulses in the visible and the near-IR spectral region exists for a number of applications, especially in the area of multi-photon microscopy. Ti:Sapphire lasers are the most commonly used laser for such applications, but recently frequency-doubled, mode-locked, Yb-doped fiber lasers and/or master-oscillator power-amplifier (MOPA) systems have been used to pump optical parametric oscillators (OPO) as a robust, compact and power-scalable alternative. In particular, synchronously pumped OPOs are ideal for CARS and SRS microscopy in that two temporally synchronous pulses at different and tunable wavelengths are produced.

We report on a lithium triborate (LBO) based OPO synchronously pumped by the pulse-compressed and frequency-doubled output of a MOPA system consisting of a gain-switched laser diode seed source and Ytterbium-doped fiber amplifiers. The 20ps output of the MOPA was compressed down to 4.4ps using a fused silica transmission grating with an overall throughput efficiency of 70%. The compressed output was frequency doubled in a 20mm long LBO crystal. Up to ~25W of 530nm green light was generated from 42W of fundamental power. Frequency doubled output was then used to pump the LBO-OPO. For a pump power of 17W, maximum combined signal and idler output powers of 2.5W (at 877nm) and 1.7W (at 1.3µm) were obtained from the optical parametric oscillator (the maximum signal power was 3.7W at 740nm). A signal pulse duration of ~3.2ps was measured and wide tunability from 651nm-1040nm (signal) and from 1081nm-2851nm (idler) was achieved. To the best of our knowledge this is the highest reported output power from a green pumped LBO-OPO. The gain-switched laser diode seeded MOPA has the potential to be operated between 100MHz and 1GHz, which in combination with the few-picosecond pulse duration and the near-IR tunability of the OPO is a very attractive source for nonlinear microscopy.

8433-02, Session 1

Thermal lensing characterisation of a high-radiance 946-nm planar waveguide laser

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The planar waveguide (PW) architecture is extremely well suited for weak laser transitions that are limited by thermal effects in a bulk configuration. Similar to the thin disc design, the PW provides excellent thermal management properties that ensure small temperature gradients across the active region. In addition, with an effective path length on the centimetre scale it provides high gain and long high-intensity interaction lengths with the pump radiation, and spatial-mode control in the guided dimension. Even so, in the high-power regime, in-plane thermal aberrations influence laser beam quality in this un-guided axis and ultimately limit the potential radiance scalability. In this work, we report on the characterisation of the in-plane thermal lens in an efficient high-radiance end-pumped 946nm Nd:YAG PW laser that has enabled us to scale the output power up to 29 W CW (M2 < 3) in an extended stable-resonator configuration.

In simple terms, an intra-cavity thermal lens gives rise to a change in the beam radii at the cavity output-coupler, and hence, information about thermal focal length is traceable from the output beam propagation parameters and knowledge of the cavity configuration. Our approach utilised the measurement of near- and far-field output intensity distributions to monitor the beam parameter product and beam size at a plane-output-coupler of the laser cavity. Consequently the varying cavity q-parameter was characterised with respect to the induced thermal lens. With the appropriate experimental settings, we determined the lensing effect at different pumping levels up to an incident power of 86.5 W, where the pump light was end-coupled into the 2 cm long double-clad (polycrystalline spinel/YAG/Nd:YAG) waveguide with focused beam radii of 34 µm × 530 µm, for which the maximum thermal lens was < 500 mm. These results are in good agreement with simulations of the thermal gradients within the PW structure.

8433-03, Session 1

Comparison of different wavelength pump sources for Tm subnanosecond amplifier

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With the increasing interest on fiber lasers operating at 2 µm there is a growing demand on amplifiers based on thulium doped fibers. These fibers are traditionally clad pumped at around 793 nm with high brightness multimode laser diodes. However in many cases the relatively long fiber required for clad pumping is not an option as in pulsed applications Self-Phase Modulation (SPM) that is proportional to the fiber length can cause unwanted spectral distortions. For this reason sometimes it is preferable to core pump the Tm doped fibers. These fibers have two major absorption bands that are interesting for core pumping. One of them is around 1.2 µm and another one is around 1.6 µm. The first can be targeted by Raman shifted ytterbium based fiber lasers while the other fits for erbium fiber lasers.

In our research we have amplified sub nanosecond pulses at 1980 nm up to a few µJ in an all-fiber configuration. For the targeted power levels, SPM can be a limiting effect, so we have focused our work on core-pumped Tm amplification. Since the literature is not so extended for core pumped Tm doped fibers and especially not for sub-nanosecond pulsed applications, we decided to try pumping the fiber at different wavelengths to find the optimum. As we have self developed various single mode Raman and erbium fiber lasers running in the 1.2-1.3 µm and in the 1.5-1.6 µm bands respectively, with more than 10 W output power available, we have studied the impact of the pump wavelength on sub-nanosecond pulses amplification in Tm doped fibers. We would like to present the performance of these pump wavelengths for amplification in terms of slope efficiency and maximum SPM-free output power. We would also compare our results to a double clad fiber amplifier pumped at 793 nm.

8433-04, Session 1

Modeling and measurement of ytterbium fiber laser generation spectrum

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A generation spectrum of a fiber laser becomes broader with increasing generation power. The spectra are rather narrow at low power and become comparable with laser cavity fiber Bragg gratings (FBG) width at high power. It has been shown that the spectral broadening of a fiber laser can be described analytically if the generation spectrum is much narrower than the FBG width. The developed theory considers independent generation of large number of longitudinal modes in a fiber laser. The theory has been compared with experiment. Double clad Yb-doped fiber laser of up to 10 W output power is used in the experiment.

Scanning Fabry-Perot interferometer with resolution down to 1.2 pm is applied for accurate spectral measurements. At power level less than 1 W a self-sustained pulsation regime accompanied by a narrow-line self-sweeping is observed. Observation of the regime has been recently described by our group in [I.A. Lobach et. al., Opt. Express 19, 17632-17640 (2011)]. At higher power a quasi-CW generation regime with multiple longitudinal modes is established. At the transition the power spectral density is considerably reduced and linewidth is broadened from the value of interferometer resolution to ~10 pm value. Investigation of the regime shows linear increase of the generation width up to 35 pm with generation power growth from 1 to 10 W. Slope of the dependence has excellent agreement with the theory, but an additive quantity ~6 pm should be added to describe an absolute value that makes significant contribution at low powers. It has been shown that at low powers a spacial hole burning has to be taken into account. Theoretical model describing the hole burning effect for multimode cw generation has been also developed. After inclusion of the hole burning effect the model starts to agree quantitatively with the linewidth measurements both at low and high powers.

8433-05, Session 1

Dual-wavelength operation of continuous-wave and mode-locked erbium-doped fiber lasers

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In this work we carry out a numerical and experimental study of double-wavelength operation of an erbium-doped figure-eight fiber laser including a multiple-bandpass optical filter. Both continuous-wave and mode-locked pulsed operations are considered. In the continuous-wave regime, stable long-term operation at two closely spaced wavelengths is only obtained if fine adjustments of the cavity losses are performed for each wavelength. In the mode-locked regime, mechanisms involving the filter losses and the nonlinear transmission characteristic of the nonlinear optical loop mirror contribute in principle to stabilize dual-wavelength operation, allowing less demanding cavity loss adjustments. In this regime, the issue of synchronization between the pulse trains generated at each wavelength adds an additional dimension to the problem. In presence of cavity dispersion, the pulses at each wavelength tend to be asynchronous if the wavelength separation is large, however they can be synchronous in the case of closely spaced wavelengths, if cross-phase modulation is able to compensate for the dispersion-induced walkoff. We believe that this work will be helpful to guide the design of multiple-wavelength fiber laser sources, which are attractive for a wide range of applications including Wavelength Division Multiplexing transmissions, signal processing and sensing.

8433-06, Session 2

High-performance wavelength tuning of a mid-infrared solid state laser using a resonant diffraction grating

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Controlling and tuning the emission wavelength of lasers with a broad gain spectrum has been a widely researched topic already for many decades. Ideally the tuning element used in the laser resonator should feature both a low insertion loss and a high wavelength selectivity. These two characteristics can be combined in a diffraction grating that relies on “resonant diffraction.” This type of grating consists of a dielectric multilayer structure which through interference effects can establish a close-to-100% diffraction efficiency along the -1st order under Littrow mounting. Such a resonant diffraction grating can be implemented in a laser resonator as an end mirror reflecting incident rays in the same direction as they originated from, and allows tuning the laser wavelength through tilting of the grating. Since this type of tuning element can be manufactured using almost any dielectric material, it can be designed for virtually any wavelength region, including the rather “exotic” mid-infrared which features a multitude of applications in e.g. spectroscopy and biomedicine.

In this paper, we report the first demonstration of resonant-grating-based laser wavelength tuning in the mid-infrared spectral domain and with Littrow mounting of the grating. We show for a mid-infrared Cr:ZnSe solid-state laser that this tuning technique is much more wavelength selective than prism-based tuning, while inducing very low cavity losses (around 2%) which are at least two times smaller than in the case of a standard metal-coated grating. Furthermore, the resonant grating allows tuning the Cr:ZnSe laser over as much as 400 nm around a center wavelength of 2.38 µm. This shows the potential of employing Littrow-mounted resonant diffraction gratings for controlling and tuning the emission wavelength of lasers emitting in the mid-infrared spectral domain and other wavelength regions.

8433-07, Session 2

Compact and efficient Cr:LiSAF laser pumped by one low-cost single-spatial-mode diode

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The Ti:Sapphire gain medium has an ultra-broad emission bandwidth which facilitates tunable laser operation in the 680-1180 nm region. However, the current cost of Ti:Sapphire lasers sets a barrier to its widespread use. As the most promising alternative to Ti:Sapphire, Cr:LiSAF also possesses a broad emission spectrum around 850 nm, enabling generation of pulses on a 10-fs level. Moreover, the broad absorption band of Cr:LiSAF around 650 nm allows direct diode pumping by low-cost laser diodes. In this talk, we will present a minimal-cost Cr:LiSAF laser that is pumped by one single-spatial-mode diode. The pumping system (diode, diode driver, and the diode holder) has a total cost of about $600 and provided 130 mW of diffraction-limited pump power around 660 nm. The entire Cr:LiSAF laser system has an estimated total material cost below $5k, a footprint of about 20 cm x 35 cm, does not require cooling and can be driven by batteries, making the system ideal for applications that require portability. In continuous wave (cw) laser experiments, we have demonstrated lasing thresholds as low as 2 mW, slope efficiencies as high as 52%, output powers up to 58 mW, and a record tuning range extending from 780 nm to 1110 nm. In cw mode-locked operation, using a 0.5% output coupler, 100-fs pulses with an average power of 38 mW, and with an optical spectrum centered around 865 nm have been obtained at a repetition rate of 235 MHz. With a more compact cavity and using a 0.1% output coupler, 70-fs pulses with an average power of 20 mW have been obtained at a repetition rate of 509 MHz. We believe that this portable, minimal cost Cr:LiSAF laser system might be an attractive source for applications like amplifier seeding that do not require high average output power levels.

8433-08, Session 2

Self-induced laser line sweeping and self-pulsing in double-clad fiber lasers in Fabry-Perot and unidirectional ring cavities

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Rare-earth doped fiber lasers are subject to instabilities and various self-pulsation regimes that can lead to catastrophic damage of their components. The self-pulsation regimes have been attributed, e.g., to reabsorption in an unpumped part of the active fiber, Raman and Brillouin scattering processes, ion pairs formation and external perturbations like pump instabilities. An interesting self-pulsing regime accompanied with laser line drift with time, so called self-induced laser line sweeping (SLLS) was described in detail recently [1,2]. The main characteristic of this effect is movement of laser line from shorter to longer wavelength, spanning over large interval of several nanometers, and instantaneous bounce backward. Period of this sweeping is usually quite long, of the order of seconds. This spectacular effect was attributed to spatial-hole burning caused by standing-wave in the Fabry-Perot cavity. Authors of Ref. 1 also noted that the effect was briefly mentioned in our earlier paper [3], where such a laser wavelength drift with time was observed in a relatively broad range of about 1076 -1084 nm in ring ytterbium-doped fiber lasers (YDFLs).

In the paper we present experimental investigation of the SLLS in two different fiber laser configuration : the Fabry-Perot cavity and the ring cavity. We confirm that the qualitative theoretical model developed in [2] for explaining SLLS in Fabry-Perot cavity can be used also to explain the SLLS in ring fiber lasers. In our unidirectional ring cavity, the spatial hole burning in YDF was caused by relatively weak interference of the laser signal with parasitic reflection from the output fiber coupler. We present the dependence of the characteristics of the SLLS, namely the range of pump powers where the SLLS occurs, wavelength range of laser line sweeping and the sweep rate on the laser cavity setup and the pump wavelength. Although the SLLS is an undesired effect in the YDFL intended for cw mode of operation, this effect may find useful applications, e.g., in interrogation of optical fiber sensor systems. Indeed, the cavity and pump power regions of YDFL can be optimized to provide relatively wide and stable SLLS output. Particular advantage of such a swept source is its simplicity as it does not require any external driving electronics, apart from the pump laser diode driver.

References:

[1] A. Kir'yanov, and N. Il'ichev, "Self-induced laser line sweeping in an ytterbium fiber laser with non-resonant Fabry-Perot cavity", Las. Phys. Lett., 8:305-312, 2011.

[2] I. A. Lobach, S. I. Kablukov, E. V. Podivilov, and S. A. Babin, "Broad-range self-sweeping of a narrow-line self-pulsing Yb-doped fiber laser," Opt. Express 19, 17632-17640, 2011.

[3] P. Peterka, J. Maria, B. Dussardier, R. Slavik, P. Honzatko, and V. Kubecek, "Long-period fiber grating as wavelength selective element in double-clad Yb-doped fiber-ring lasers", Las. Phys. Lett. 6:732-736, 2009.

8433-09, Session 2

Study of tunable resonances in laser beam divergence and beam deflection

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New, fundamental resonant property of laser resonators is theoretically predicted and experimentally demonstrated.

In the first order of perturbation calculation a small perturbation of the complex q-parameter of the fundamental transversal mode light beam in a laser resonator changes only complex phase after a round trip. The value of the complex phase change depends only on the so called stability parameter of a laser resonator which can be defined as a half of the trace of the round trip ABCD-matrix [1]. This phase shift after a round trip results a resonant behaviour of the divergence of the light beam in the laser resonator. The resonance frequency can be continuously tuned from zero to the round trip frequency of the laser resonator, and its transposed frequencies by the multiple of the round trip frequency are also resonant. In astigmatic resonators we may have different resonance frequencies of the divergences in different directions.

The resonant behaviour was experimentally demonstrated with a longitudinally pumped astigmatically compensated Ti:sapphire ring laser. The ring resonator arrangement was chosen just to have a laser resonator in which any effect can change the q-parameter of the light beam only once per round trip just as is the case in our simple model. We changed the stability parameter of the laser resonator by longitudinally moving one of the concave folding mirrors. Using a knife-edge to stop most of the output beam and only its small part was measured with a fast linear detector. The signal was observed by a digital oscilloscope (Agilent, 2.5 GHz bandwidth). The AC-coupled input was inspected at the smallest measuring limit (1 mV) with 1 GHz sampling frequency, a Fourier-transform was taken of 32768 sample points. The Fourier-spectrum was averaged many times to reduce its noise. We observed resonant behaviour in the noise of the detected signal. The observed resonance was 3-10 dB above the noise-background of the measuring system (approximately -90 dBm). Measuring real-valued signals, if we observe resonance at a frequency value than we also observe resonance at the complement frequency up to the round trip frequency. The observed dependence of the frequency of the resonance on the stability parameter of the laser resonator was in good agreement with the theory.

Another continuously tunable resonance connected to the tilt angle of the output beam was also observed. This resonance is detectable also when the knife edge was positioned at the middle of the light beam.

The existence of these resonances makes the theories of different laser phenomena (for example the Kerr-lens mode locking) be reconsidered. One of the possible applications of these resonances is an approximate mapping tool of the stability region.

References:

1. A. E. Siegman, Lasers, University Science Books, Mill Valley, California, 1986.

8433-10, Session 2

High-efficiency Q-switched and diffraction-limited Nd:YLF side-pumped laser

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To obtain a laser resonators set-up that permits power scalability associated with high beam quality and high efficiency is still a major goal in the laser cavity design field. Although longitudinal-pumping has been demonstrated to be a good design to obtain high beam quality and efficiency, it has severe limitations regarding the power scalability due to the thermal fracture limit of the active medium. Side-pumping technology permits higher pumping power and scalability but is generally associated with lower beam quality and efficiency. There are only a few power scalable designs that permit good beam quality and high efficiency using the side-pumping technique, most of which are complex configurations that require specially tailored active media.

In this work we demonstrate a highly efficient, side-pumped, all-solid-state Nd:YLF laser pumped at 792 nm that uses 1mol% neodymium doping. Up to 47% optical-to-optical conversion efficiency was obtained from a mode-controlled (stable TEM00 is achieved without additional losses) laser emitting at 1053nm, to the best of our knowledge, the highest efficiency ever reported for a side-pumped Nd:YLF laser. We obtained up to 15.1W of qcw peak output power at 1053 nm by pumping with 32 W from a TM-polarized diode that was focused into the crystal (spot size 5mm x 0.1mm). Fundamental mode oscillation was extracted by using a three-mirror cavity comprised by a folding mirror of 75 cm radius of curvature, a plane HR end mirror and a plane output coupler with 40% transmission. We also report on passively Q-switched pulses of 2.3 mJ at 71 Hz repetition rate and 19 ns pulse duration with this same cavity set-up.

8433-48, Poster Session

Eye-safe pulsed kW-peak power high-repetition rate all-fiber MOPA source

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Pulsed laser sources operating in the so called eye safe wavelength region (> 1500 nm) are very attractive for numerous applications in free space and satellite optical communication, remote sensing, range finding, LADAR systems. All these applications require suitable peak power of generated pulses, which is very often quite difficult to achieve in simple generators. Therefore, Master Oscillator Power Amplifiers (MOPAs) utilizing low power seed oscillators followed by a cascade of erbium and erbium/ytterbium amplifiers are usually adopted.

In fiber MOPA configuration, a low power semiconductor single-mode source is modulated with precise control of output parameters and then amplified in a series of amplifiers to the energy/peak power level required by the particular application. The combination of low power seed laser and fiber power amplifiers including necessary passive components) gives the chance to obtain compact, robust, versatile and efficient pulsed all-fiber sources with the flexibility in choosing output parameters (repetition rate, pulse duration, line width and even pulse shape).

The paper presents the all-fiber laser system based on MOPA configuration, generating stable single nanosecond pulses with kW level peak-power. It generated pulses of changeable duration in the range of (0.5-5) ns at the repetition of (0.2-2) MHz. The total signal gain of up to 57 dB and the maximum average output power of over 33.7 dBm were demonstrated when the total pump power of the booster amplifier was 8.9 W. For 200 kHz repetition rate 1.2-ns pulses with the energy of 4 uJ were achieved which corresponds to 3.4 kW peak-power.

8433-49, Poster Session

Millijoule-level 20 ps Nd:YAG oscillator-amplifier laser system for investigation of stimulated Raman scattering and optical parametric generation

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The most common approach to a picosecond laser source with output energy in milijoule level is a continuously pumped mode locked oscillator with single pulse selector followed by a regenerative amplifier. These systems can operate with repetition rates up to 100 kHz with single pulse duration around 10 ps. For many applications, as for example laser ranging, lasers operating at repetition rates below 1 kHz with longer pulse durations are more suitable. Such pulses can be obtained from passively mode-locked lasers with pulsed pumping, where the microjoule pulses are generated directly from oscillators and simple single or double pass amplifiers are sufficient for additional pulse amplification.

Research and development of such laser is the subject of this contribution. The laser system consisted of a pulsed diode pumped oscillator based on the highly-doped Nd:YAG slab in bounce geometry and passively mode locked by a semiconductor saturable absorber mirror. Using the cavity dumping technique, 20 ps pulses with the energy of 25 uJ and Gaussian spatial beam profile were generated directly from the oscillator at the repetition rate up to 100 Hz. For applications requiring more energy the pulse amplification was studied using either an identical highly doped Nd:YAG module in bounce geometry or flashlamp pumped Nd:YAG laser rod.

Using compact all diode pumped oscillator-amplifier system the 200 uJ pulses were generated. The flashlamp pumped 100 mm long Nd:YAG amplifier enabled to obtain higher energy. In the single pass configuration the pulse was amplified to 3 mJ, using the double pass configuration the pulse energy was further increased to 11 mJ with the duration of 25 ps at 10 Hz. Application of the developed laser system for investigation of stimulated Raman scattering in diamond and also for optical parametric generation in CdSiP2 will be also reported.

8433-50, Poster Session

Ultrashort pulse amplification in the induced optical anisotropic medium

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The possibilities for the medium's coherent response accumulation method are studied in order to amplify the rotation of probe beam polarization in two-photon resonance conditions.

We discuss a gas medium of three-level atomic systems, with the first excited energy level splitted into two magnetic sublevels, in a combined "probe+pump" field. This model is the most convenient for discussions with alkali metals. Here the far off the resonance, monochromatic, strong pump field connects the excited doublet with the higher excited energy level and the far off the resonance, weak probe field connects the ground state of the atom with an excited doublet . All the calculations are done in two-photon ("probe+pump") resonance conditions.

Here we've received an analytical expression for the output probe field in the dipole and rotated wave approximation.

We have shown that by coherent shifting of input probe field's phase from 0 till and vice-versa for the rotated component of the output probe field we can get an isolated, about 5 times narrowed light impulse with more than 16 times amplified intensity.

8433-51, Poster Session

Transfer capability of 3-5 um radiation by hollow glass waveguide

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The aim of this work was delivery investigation of 3 - 5 um laser radiation by a hollow glass waveguide. The waveguide was formed by a supporting fused silica glass capillary tube with a silver layer deposited on the inside wall. As an inner dielectric material film, a cyclic olefin polymer was used. The primary parameters of the sample investigated were the inner/outer diameter 700/850 um and the length up to 110 cm. As radiation sources, three lasers generating in mid-infrared spectral region were designed and constructed. The flash-lamp pumped Er:YAG laser operated at 2.94 um wavelength. The second system was 4.3 µm Dy:PbGa2S4 laser. Its coherent pumping was performed by the flashlamp pumped Er:YLF laser generating at 1.73 um wavelength. The third laser emitting at 4.45 um was based on Fe:ZnSe active medium pumped by electro-optically Q-switched Er:YAG laser radiation. The study presented describes transfer capability of 3 - 5 um radiation by COP/Ag hollow glass waveguide. The delivery efficiency and spatial structure were investigated. The transmission measured reached 84 %, 58 %, and 64 % for Er:YAG (2.94 um), Dy:PbGa2S4 (4.3 um), and Fe:ZnSe (4.45 um) laser systems, respectively. The spatial beam structure transferred was similar for all systems. The laser delivery system based on COP/Ag hollow glass waveguide can be useful for some mid-infrared radiation medical and industry applications.

8433-52, Poster Session

Tunable Fe:Cr:ZnMgSe gain-switched mid-IR laser operating at room temperature

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The goal of this work was to design and investigate the gain switched new FeCr:ZnMgSe laser operating at the room temperature. The pumping was provided by the electro-optically Q-switched Er:YAG laser with the oscillation wavelength of 2.937 um matching the local maximum of the FeCr:ZnMgSe absorption. The Q-switched operation was obtained by the Brewster angle cut LiNbO3 Pockels cell placed between the rear mirror and the laser active medium. The output radiation parameters were: the energy of 10 mJ, pulse duration of 120 ns, and repetition rate 1 Hz.

The pump radiation was directed into the Fe:Cr:ZnMgSe crystal placed inside the 16 mm long hemi-spherical cavity formed by the dichroic pumping mirror (T=86% at 2.94 um and R=100% for 4-5 um) and the output coupler with the reflectance R=95% at 4-5 um and radius of curvature r = -500 mm. The maximum output Fe:Cr:ZnMgSe laser energy was 160 uJ corresponding the slope efficiency 4% (with respect to absorbed energy). The generated radiation wavelength was 4.8 um with the linewidth of 100 nm (FWHM). The output beam spatial profile was approximately Gaussian in both axes.

Laser tuning properties were investigated by the Lyot filter (MgF2 plate, 2 mm thick) inserted into the resonator providing the tuning range from 4.5 to 4.9 um. The results were compared with the Fe:ZnSe crystal operated at the same conditions.

8433-53, Poster Session

A highly efficient resonantly pumped Ho:YAG laser

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The paper presents the Q-switched Ho:YAG laser pumped by a linearly polarized 20W CW@1908 nm Tm:fiber laser, generating mJ pulses at the wavelength of 2090 nm. A high slope efficiency (over 50%), optimization of energetic and spatial parameters of the laser beam for the whole range of pump power were demonstrated. The performance of this laser was investigated for operation both in free running and acousto-optic Q-switching regime. The laser output characteristics were performed taking the pumping beam and resonator parameters, reflectance of output couplers for free running regime and the repetition rate for Q-switching regime into account.

8433-54, Poster Session

Ion argon-krypton laser for new medical applications

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Ion gas lasers filled with pure argon or krypton are often used in medicine. In some wavelength ranges (for example yellow range) ion lasers still have no serious competitors. Moreover in last years the number of possible laser applications in medicine increased significantly. Most applications requires specific wavelength range. For example green range (about 530 nm) is optimal for retina photocoagulation, yellow range (about 570 nm) is optimal for photocoagulation of macula region, red range (about 650 nm) is optimal for photodynamic cancer therapy. Due to number of available laser wavelengths of argon and krypton lasers, laser filled with mixture of both gases could be interesting universal medical laser source. However output power value of some interesting in medical point of view laser wavelengths of this laser may be insufficient for certain applications.

In this paper will be presented results of authors' investigations in the area of ion lasers which create new possibilities for use of lasers filled with mixture of argon and krypton as well other noble gases in medical applications. Developed by authors pulse and multi-pulse ion laser supply regime in connection with observed and described by authors the effect of laser output power increase in presence of noble gas admixtures allows to achieve radiation power values unavailable in typical ion lasers filled with pure argon and krypton and operated with standard continuous power supply regime. The magnitude of output laser power value increase which was obtained by authors could be satisfactory for certain medical applications.

Authors will present new possibilities of argon-krypton ion laser usage for medical purposes with analysis of potential use of selected laser wavelengths for specific medical applications, especially dermatology and ophthalmology.

8433-55, Poster Session

Influence of noble gas additions on the output power value of krypton ion laser

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Ion gas lasers, especially argon and krypton ion lasers are important sources of high quality laser radiation in the visible range as well in the ultraviolet range. The maximum output power in this type of lasers generally depends on discharge current value. The discharge current is limited mainly by discharge tube thermal durability and the laser tube cooling efficiency. As result the output power of typical commercial argon lasers is also strictly limited and can not achieve higher values required in certain applications.

In this paper authors will present the phenomenon of advantageous influence of noble gas additions other than active gas of particular ion laser on the laser output parameters. Authors of the paper have observed that small additions of argon to the krypton discharge causes significant increase of the krypton ion laser output power on some krypton laser lines. For example the presence of about 20% of argon in argon-krypton mixture leads to increase of the krypton laser output power for about 30-40% compared to output power in the same laser filled with pure krypton and operated with identical power supply conditions. The value of power increase depends on laser line wavelength, mixture composition, pressure and discharge current value.

Authors will describe results of analysis of this phenomenon and will try to explain it. Presented measurements for individual laser lines was performed in full range of gas pressures, mixture compositions and supply conditions.

This effect could be useful in these applications of ion lasers where the power value of generated laser radiation is the most important parameter. Authors will continue their researches with other gas additions and other active gases.

8433-56, Poster Session

Pr,Ce:YAlO3 crystal properties under UV-radiation exposure

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In the current period, materials doped with Pr3+-ions attract a great deal

of attention in terms of visible-laser-source realization because Pr3+-ion energy level diagram offers several laser transitions practically throughout the whole visible spectral range up to the near infrared. Efficient Pr-lasers have been demonstrated in various fluoride and oxidized laser hosts. In comparison to Pr-fluorides, Pr-oxides excel in higher hardness, thermal conductivity, and mechanical and chemical stability.

As came out in one of our past experiments concerning the Pr:YAlO3 (Pr:YAP) active material, UV-radiation has an adverse effect for lasing action due to the crystal solarization. So, co-doping of this material by Ce3+-ions having broad absorption-bands in the UV-region has been proposed for crystal property improvement in terms of color-center formation. The Pr,Ce:YAP absorption-spectrum investigation under UV-radiation exposure, in comparison to the Pr:YAP one, is reported in this contribution. Moreover, lasing properties of these two materials under the GaN-diode pumping are summarized.

In our experiment, the Pr,Ce:YAP active medium (5 × 5 mm in dimensions) with the concentration 0.6 at. % and 0.1 at. % of Pr/Y and Ce/Y, respectively, was used. It was inserted inside the elliptical silver-coated laser-cavity and gradually (in several different time-intervals) irradiated by UV-radiation presented in flash-lamp pulses (energy 100 J). The rate and degree of the Pr,Ce:YAP absorption-spectrum altering were consecutively recorded. The same measurements were carried out for the Pr:YAP sample with the same dimensions and Pr3+-ion concentration, and subsequently compared with the Pr,Ce:YAP results. As transpired, Ce3+-ions incorporated in the Pr:YAP matrix have a positive influence on the crystal resistance against the UV-radiation, especially in the crystal-absorption-band regions. It indicates that the direct flash-lamp pumped laser system based on Pr-ions in YAP matrix should be possible to realize. The verification of this assumption is underway.

8433-57, Poster Session

Laser turn-on behavior in organic VECSELs

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Organic lasers offer the promise to build compact, inexpensive, broadly tunable solid-state lasers in the visible range, with potential applications in spectroscopy, bio/chemo sensing or short-haul data telecommunications. Among existing laser architectures of optically-pumped organic lasers, external-cavity resonators enable the highest conversion efficiencies, excellent beam quality, power scalability and versatility due to the open cavity. Recently, we reported on an open-cavity laser architecture using a thin film of dye-doped polymer as the gain medium, named Vertical External Cavity Surface-emitting Organic Laser (VECSOL). The laser architecture consists of a highly-reflective plane mirror onto which a film of PMMA doped with e.g. Rhodamine 640 was directly deposited by spin coating. A remote output coupler closed the cavity; under pumping by a frequency-doubled Nd:YAG laser at 532 nm ; the structure enables reaching very high conversion efficiencies (>50%) with a diffraction-limited beam and a wavelength-tunable output.

In this paper we provide a simple theoretical framework to study the laser turn-on dynamics and eventually optimize the laser performance, based on the Statz-deMars coupled rate equations. The simulations are confronted to the measured efficiency curves and the experimental pulse shapes of the pump and laser beam, recorded with the same fast photodiode at zero optical delay. A shifting and a broadening of the laser pulse (of a few ns) with respect to the 0.5-ns-long pump pulse are observed, discussed within the framework of the simplified model, and interpreted as the result of a pulse buildup time being of the same order of magnitude as the photon lifetime in the cavity. The optimal pulse pump duration can be estimated at a given pumping level. The VECSOL is then characterized with different pump pulse durations (0.5ns, 7ns and 25 ns) and the efficiency compared to the model. Indications towards an optimized device can then be drawn.

8433-58, Poster Session

Excited-state absorption measurements of Tm-doped crystals

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The excited-state absorption (ESA) spectra from the long-lived 3F4 energy-level of several crystals doped with trivalent thulium (Tm3+) ions have been measured using a pump-probe technique employing high-brightness narrowband (FWHM ~15 nm) light emitting diode (LED) as the probe. Our aim is to determine the strength of ESA channels at wavelengths addressable by commercially available laser diodes around 630-680 nm, pivotal for building waveguide upconversion lasers. The favorable lifetime of the 3F4 energy-level and negligible ground-state absorption for the red-wavelength second-step excitation, ensures a direct and efficient excitation route for a dual-wavelength pumping scheme of the thulium ion, which will enable blue-green laser emission from its 1G4 manifold.

ESA measurements in the red spectral region were conducted at room temperature utilizing the pump-probe technique. The advantage of the LED probe over a broadband incandescent lamp is that stimulated-emission at the probe wavelength can be eliminated, simplifying the analysis of the measurement and the determination of the magnitude of the ESA cross-section. Four Tm-doped crystalline hosts Y3Al5O12 (YAG), YAlO3 (YAP), LiYF4 (YLF), and KYGdLu(WO4)2 (KYGdLuW) were investigated, with polarized ESA spectra measured for the non-isotropic samples. Excitation of the Tm3+ ions into the intermediate 3F4 manifold was achieved via non-radiative and cross-relaxation energy transfer from the 3H4 manifold, pumped by a current-modulated fibre-coupled GaAs laser diode operating at ~790 nm. To ensure that ESA at all wavelengths of interest were resolved, the LED's spectra were tuned via the modulated drive-current amplitude and junction temperature. As such, with direct pump and probe modulation, we eliminated the need for mechanical choppers, simplifying the optimization of frequency-resolved ESA measurements needed to isolate the other possible ESA transition (3H4 → 1D2). Vastly improved ESA spectra have been obtained with respect to those reported in the literature.

8433-59, Poster Session

Tunability of laser based on Yb-doped hot-pressed CaF2 ceramics

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The aim of presented study was an investigation of tunability of diode pumped laser based on hot-pressed Yb:CaF_2 ceramics. The tested Yb:CaF_2 sample was in the form of 3.5 mm thick plane-parallel face-polished plate (without AR coatings). The Yb^{3+} concentration was 5.5 %. A fiber (core diameter 200 <font face=”symbol”>mm, NA =0.22) coupled laser diode (LIMO, HLU25F200-980) with emission at wavelength 976 nm, was used for longitudinal Yb:CaF_2 pumping. The laser diode was operating in the pulsed regime (4 ms pulse length, 20 Hz repetition rate). The duty-cycle 8 %ensured a low thermal load even under the maximum diode pumping power amplitude 20 W (crystal sample was only air-cooled). This radiation was focused into the crystal (pumping beam waist diameter <font face=”symbol”> ~ 170 <font face=”symbol”>mm). The 145 mm long semi-hemispherical laser resonator consisted of a flat pumping mirror (HR @ 1.01<font face=”symbol”>-1.09 <font face=”symbol”>mm, HT @ 0.97 <font face=”symbol”>mm) and curved (r=150 mm) output coupler with a reflectivity of <font face=”symbol”> ~ 98 % @ 1.01<font face=”symbol”>-1.09 <font face=”symbol”>mm. Tuning of the ytterbium laser was accomplished by using a birefringent filter (single 1.5 mm thick quartz plate) placed inside the optical resonator at the Brewster angle between the output coupler and the laser active medium. The extremely broad and smooth tuning was obtained. The laser was continuously tunable over <font face="symbol"> ~ 66 nm (from 1015 nm to 1081 nm) and the tuning band was mostly limited by free spectral range of used birefringent filter. The tunability FWHM was 40 nm corresponding bandwidth 10 THz results in fourier limited gaussian pulse width <font face="symbol"> ~ 40 fs (FWHM). The maximum output power amplitude 0.68 W was obtained at wavelength 1054 nm for absorbed pump power amplitude 6 W. The laser slope efficiency was 15 %.

8433-60, Poster Session

Bulk Er:YAP and Er:Yb:YAP optical emission studies for eyesafe laser applications

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High-peak-power and high rep. rate Erbium-ion laser systems emitting in the eyesafe region (1.4 to 1.7microns), will require efficient crystalline hosts as alternatives to glass. Thus, with the objective of evaluating the lasing potential of Erbium ions in YAP and designing a diode-pumped pulsed eyesafe-laser prototype, we investigated the 1.5-micron emission properties of Er-doped and Er-Yb-codoped YAP Crystals. Results were compared with similarly doped YAG crystals, which have alredy demonstrated efficient diode-pumped lasing action on the same transition in the eyesafe region.

Emission spectra of Er-doped YAP crystals were taken using a nanosecond OPO as tunable pump source. A Near-IR monochromator with InGaAs detector was used to record the emission spectra. Er emission in YAP shows a continuous broad band ranging from 1460nm to 1650nm, with a main peak at 1545nm and a secondary peak at 1608 nm. Temporal emission characteristics were also studied, specifically Er emission-lifetimes and Yb-Er excitation transfer times in the case of co-doped crystals.

Excitation spectra were taken by fixing the emission detection wavelength at one of the observed peaks (1608 or 1545nm) and then spectrally scanning the pump OPO beam. At each pump wavelength, the corresponding emission signal at the selected peak wavelength was recorded. These spectra revealed two groups of excitation bands suitable for diode-pumping, one around 800nm consistion of several narrow peaks, and another wide continuous band peaking at 970-nm.

Finally, YAP results were compared with analogous measurements on Er:Yb:YAG, which has already demostrated efficient lasing action at 1.65 microns.

Summarizing, Er-doped YAP crystals have pump bands lying in the 800-nm and 970-nm regions, capable of utilizing standard inexpensive laser pump diodes. The eyesafe-emission band peaks at 1545-nm (the accepted "standard" eyesafe wavelength similar to the conventional Er:Glass), but the band extends beyond 1.6 microns (where for e.g. lasing action in similarly-doped YAG has been demonstrated). The eyesafe Er emission band in YAP is broad and continuous, potentially offering the possibility of tunable and/or ultrafast systems based on such material.

8433-61, Poster Session

Energy transfer analysis of Tb3+ and Yb3+ ions doped in borosilicate glass

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The CW laser oscillation at 0.54 μm has been achieved for Tb3+-doped optical fibers. A shorter wavelength laser with high power is needed to pump Tb3+ ions directly and it is hindered by the excited state absorption to the 5d levels. Thus cooperative energy transfer from two Yb3+ ions cooped with Tb3+ ions to an Tb3+ ion is the promising pumping scheme. In this study we have analyzed the energy transfer efficiencies between Tb3+ and Yb3+ doped in borosilicate glass in detail.

In ordinal models used for analysis of energy transfer between rare-earth ions in glass are assumed that the doped rare-earth ions are dispersed homogeneously in the host material. According to such a model, we could not obtain well fitted results for decay curves of emissions from Tb3+ and Yb3+ doped in borosilicate glass. Therefore we assumed that Tb3+ and Yb3+ ions are dispersed non-uniformly in the borosilicate glass. In this case, a Tb3+ (Yb3+) ion being nearby Yb3+ (Tb3+) ions contribute to the energy transfer but isolated rare-earth ions do not contribute.

The rare-earth ions are classified to two categories depending on the contribution to the energy transfer or not and the rate equations of them are constructed. The fitting results were well reproduced the measured decay curves. It was clarified that 2-13 % of Tb3+ and 14-42 % of Yb3+ ions contribute to the energy transfer.

8433-62, Poster Session

CaF2-TmF3 ceramics a potential active medium for 2 μm lasers

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Rare-earth-doped ceramic materials are of interest as active laser media. Advantages of ceramic laser materials include the following: fabrication of large size elements, large concentration and homogeneous distribution of dopants, possibility to obtain a new composition as an optical media, which is difficult or impossible to prepare in the form of single crystals. For example, the most-developed laser ceramics based on oxide materials (Y2O3 and Y3Al5O12).

The analysis of development tendencies of modern photonics shows that the nearest progress in this area will be connected substantially with devices based on the fluoride materials, because of fluorides having the following properties: wide transparency window from 0,16 up to 11 microns; "short" phonon spectra inhibiting the harmful effect of multiphonon relaxation in radiation transitions of doping ions, ease high level (up to 1021 sm-3) doping by active rare-earth ions; best mechanical properties and high moisture resistance compared to the other classes of substances this a wide optical transmission window; high thermal conductivity.

Tm:CaF2 ceramic samples were prepared by a severe plastic deformation technique.

Tm3+-doped CaF2 ceramic samples have been studied by optical spectroscopy, SEM and AFM. The absorption and luminescence spectra of the Tm:CaF2 ceramic and single crystals have been measured. The results demonstrate that the 3H6→1G4, 3H6→3F2 + 3F3, 3H6→3H4, 3H6→3H5 and 3H6→3F4 absorption bands and the 3F4→3H6 luminescence band in the ceramic are similar in shape to those in the crystals.

We have estimated the shape of the gain band for the two-micron laser transition 3F4→3H6 at different relative population inversion parameters. The gain band of the crystals and ceramic extends from 1700 to 2000 nm.

8433-63, Poster Session

Simulation of the influence of atmospheric conditions on low-cost optical free-space link

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The team of authors was concerned in the development and construction of low-cost free space optical link and simulations of the influence of atmospheric conditions on this link. The article contains description of electronic design and attention is also dedicated to simulations of atmospheric conditions. Gradually, the most frequently occurring atmospheric conditions and their impact on the available bit rates were tested. An integral part of the article is calculation of the energy balance of the whole link. At the end are shown images of the measured eye diagrams and samples of measured distribution of optical power using a digital camera and its processing in MATLAB.

8433-64, Poster Session

Laser-induced shock waves from structured surfaces

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Laser induced shock wave (LISW) generated at the surface of a material are well known to launch propagating dynamic pressure wave into the material that modifies state of stress within the material. We present our results on the expansion dynamics of the ablated plasma from surface of stainless steel alloy into air characterized by time resolved shadowgraphic imaging leading to an understanding of the SW propagating into the material due to momentum conservation. A machinist's scale with periodic surface structures of 30 µm depth and 240 +- 20 µm diameter having 25 and 64 lpi (lines per inch) corresponding to one and three rectangular structures, respectively, is used as a target surface. Laser pulses from frequency doubled Nd:YAG (7ns, 532 nm) with 45 mJ energy focused to a beam diameter of ~ 1 mm on the target surface are used to generate LISW. A fast ICCD camera (DH-734U, ANDOR) with 1.5 ns resolution is used to capture the time evolution of SWs into air. The SW properties from the structured surfaces were compared to that produced from plane surface under same experimental conditions. The SWs in air from a plane surface are observed to follow Sedov-Taylor solution [1] from initial time of 0.2 up to 20 microseconds. While the SWs from structured surfaces show a deviation during 0.2 - 4 microsecond time scales. The maximum velocity of the SWs has increased from 2.75 to 4 km/s with increasing number of surface structures from 25 to 64 lpi. From the measured radius of curvature of SW's (RSW), the velocity, density jump and pressure associated with the micro explosion of metal surface is estimated using Counter Pressure Corrected Point Strong Explosion Theory (CPC-PSET).

1. Ya. B. Zel′dovich and Yu.P. Raizer, Physics of SWs and High-Temperature Hydrodynamic phenomena, Dover Publications, (2002).

8433-65, Poster Session

The investigation of transient thermal effects in optical elements under high laser intensities

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The most important limitations in development of high energy and high power lasers based on solid state technology are thermal effects occurring under high intensity and high heat loads. The thermo-optical effects occurring inside output couplers, folding mirrors, output windows can significantly diminish the beam quality of high power lasers and therefore have to be investigated. The knowledge on transient thermal effects occurring inside bulk laser elements exposed on laser intensities of several dozens of kW/cm2 is of special interest for some special applications (e.g. heat capacity lasers). The aims of work were theoretical analysis of those effects occurring inside the laser mirrors and its experimental verification. The hints for choice of the best materials (from the point of view of thermal limitations) for laser windows and output couplers were pointed out. The most demanding case of materials and technology for transmissive, dichroic elements was indentified.

The special laboratory setup enabling simultaneous registration of thermo-optical effects applying shearing interferometry and wavefront sensing by means of Shack-Hartmann test was worked out. The transient as well as averaged in time thermal-optical effects occurring inside the volume of examined element as a result of surface absorption in the coatings and bulk absorption in the material can be resolved and measured. The resolution of measurements: less than 0.1 K temperature difference and thermally induced optical power of about 0.1 m-1 were demonstrated. The several laser mirrors made of BK7 and fused silica glasses were investigated in such a setup to verify the theoretical models and validate the measurement methods. One of the conclusions of this research is that even in relatively low power solid state lasers, end-pumped with power densities of 104 kW/cm2, thermo-optical effects occur in dichroic, rear mirrors and has to be mitigated by the proper design of laser cavity.

8433-66, Poster Session

Large aperture plasma electrodes Pockels cell for multi-pass amplified scheme of SGII upgrading laser

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The multi-pass amplified scheme of SGII upgrading laser is similar as that of NIF. Large aperture plasma electrodes Pockels cell (PEPC) is the key unit of this amplified scheme. The transit time that laser beam passes through the PEPC for the first time and second time is about 270ns. PEPC should switch the state between ON and OFF in 270ns. The response time of the PEPC driven by positive-negative switching pulses can not satisfy the demand of SGII upgrading laser due to the higher generator impedance. In the single-pulse-process, the low-impedance high voltage generator based on double Blumlein pulse-forming line is used to drive the PEPC. The amplitude of single pulse is up to 21kV, while the impedance of the generator is only 6.25. The theoretical charge time of the PEPC with 350mm×350mm aperture is about 54ns, and the response time of PEPC is less than 170ns in the single-pulse-process. The response time is reduced greatly. The switching efficiencies with full aperture are higher than 99.7%. The extinction contrast exceeds 381. The top width of the time window is larger than 160ns, and the bottom width is about 400ns. All the experimental results can meet the specification of SGII upgrading laser.

8433-67, Poster Session

A comparative numerical study on Yb-doped Sc2O3, Lu2O3, and YAG performance in high-power thin disk lasers

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Among the active media used in thin disk lasers, the first and the most utilized material has been Yb:YAG, with which the highest power and energy regimes have been achieved. The most interesting active doping in high power operation is these ions, because the Yb^(+3) ions exhibit very small Stokes-losses leading to very small heat generation in laser crystal. YAG is widely used as the host medium in high power lasers (in kilowatt range) because of its good thermal, mechanical, and optical properties and, also its capability to be easily grown with common methods. Recently Yb-doped ceramic sesquioxides have been generally recognized as the host media with better physical properties compared with conventionally used Yb doped materials. The highest slope and optical to optical efficiency for Yb-doped thin disk lasers has been reported in Yb:Lu2O3. Considering appropriate thermal and spectroscopic properties of sesquioxides two Scandia (Sc2O3) and Lutetia (Lu2O3) crystals have been chosen from this category and

compared in working with optimized parameters in a 1kW pumped disk laser. Optimum values of doping concentration, crystal thickness, and output coupler transmission as system parameters have calculated and compared. Using the Mont Carlo method and ray tracing in multi-pass pumping system, calculation of the absorption phenomenon in laser active medium was conducted. Laser rate equations for quasi-three level system in steady state under the resonator gain and loss equilibrium condition has been used to calculate the output power; However, re-absorption in laser wavelength considered in our model. Temperature inside the laser crystal was calculated by regarding the absorbed power density. Results were compared and evaluated by previous experimental reports. Reduction of temperature gradient in active medium can be achieved specially in Yb:Lu2O3 with optimized thickness and doping concentration in comparison with Yb:YAG. This important result leads not only to lower thermo-optical and thermo-mechanical distortions, but also to better power scaling capability. Moreover, increasing the optical efficiency by using the mentioned host materials was predicted. Using these hosts particularly Yb:Sc2O3 can reduce the number of pumping beam passes through the active medium, would led to less complicated pumping configuration and the number of optical and opto-mechanical elements without losing the absorption efficiency. Results obtained in this study reveal that Yb:Lu2O3 is a promising material which can trustfully be exploited in thin disk lasers as it has been previously used in low power regimes.

8433-68, Poster Session

Power scaling limitations in quasi-three level disk lasers

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Thin disc Yb:YAG lasers have been developed as high average power sources by Adolph Giessen in collaboration with a number of colleagues, and so far the output power in the kilowatt range has obtained. High power output and good beam quality simultaneously is achieved due to active media disc geometry and its longitudinal heat flow.

For quasi-three-level system such as Yb: YAG, the laser performance depends strongly on the temperature, because at higher temperature, the population is accumulated at lower laser level, thus the re-absorption losses increases. Quasi-three-level materials offer, on one hand, the possibility of building lasers of the highest efficiency. But on the other hand, they are hard to operate because they show a relatively high absorption of the laser-wavelength, since the lower laser level is so close to the ground state that a considerable number of the laser-ions are in the lower laser level, when the laser is operated at room temperature. Therefore, it is necessary to pump the material with high pump power density in order to reach the threshold without increasing the temperature of the crystal too much. In order to get sufficient absorption of the pump radiation in the thin crystal plates (100-300 μm) quite high Yb concentrations are necessary. At high concentration, resonant migration of the excitation energy between the Yb ions occurs. At higher doping concentrations this energy migration is fast. As a consequence, a certain portion of the excitation energy may also be transferred to impurities in the crystal lattice resulting in radiative or nonradiative de-excitation and thus decreasing the Yb-fluorescence quantum efficiency. In previous works of researchers, only the temperature dependence of the Boltzmann's thermal population functions have been applied. These models only predict the laser system operation at low Yb concentrations, because at the higher concentrations, fluorescence concentration quenching phenomenon is happened. For this reason our team have presented a numerical model which not only temperature dependence of the Boltzmann's thermal population functions and the Yb: YAG thermal conductivity coefficient have applied in the model, but also concentration dependence of the upper laser level life time is added to the dependency components. In addition to these dependences, there are other parameters that their thermal dependences are significant at laser operation. For example, the absorption and emission cross sections are two parameters that their thermal dependences affect on the absorption pump distribution and the output efficiency. For presenting an exact model, applying these dependences is necessary, so here is focused on the effects of temperature and doping concentration dependence of laser parameters on the disc laser operation. Because of considering of these dependences in the numerical model, its results are near to reality.

Numerical model consists of three main steps: 1) the calculation of the pumped distribution inside the crystal by analytical function approximation, 2) the calculation of the temperature distribution inside the crystal with finite element method (FEM), and 3) the calculation of the output power according to the pump and temperature distribution which have been calculated in the previous steps. The plane-parallel and very short length resonator is considered for the output power calculations.

By applying all the dependences, with respect to the independent state (0th iteration), the output efficiency is reduced by 25% i.e. the predicted laser output power exceeds the actual value if the temperature and doping concentration dependency of laser parameters is neglected. According to this model, if the doping concentration is increased to more than 28%, the optical efficiency begins to reduction. By using this model, through variation of designing parameters, disc thickness, number of pump beam passes, cooling fluid temperature and Yb ions concentration, we can derive the laws of disc laser power scaling. For each 1 oC reduction in the cooling fluid temperature, the output efficiency increases 2% and 8% for the pump beam passes 32 and 8, respectively. We can use this model to design the other quasi three level laser systems.

8433-69, Poster Session

Dynamic response of metals and alloys to laser-induced shock waves

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When a high energy laser beam incidents on a solid surface, atoms in the surface start vibrating by absorbing the energy of laser beam. These vibrations heat up the atoms rapidly increasing the temperature of the surface locally. Because of the rapid heating and thermal expansion, the surface of the material is compressed in time within few nanoseconds. This compression propagates through the material as a shock wave. Shock pressures as high as few tens of GPa or higher generated by explosives or planar impact devices can be generated using lasers easily with duration of shock pulse in the nanosecond time range.1 Laser generated acoustic shock waves (ASWs) are ideal for simulating a blast wave or a sonic boom in the laboratory and for studying the associated propagation effects.2,3

Laser induced shock waves in solids have important applications in dynamic response of material studies and high pressure physics. We present the measurements on the propagation characteristics of the laser generated ASWs and the vibrations aiming to understand the laser-solid interaction in real time. Laser pulses (7 ns) from second harmonic of a Nd:YAG laser (532 nm) were used to launch compression waves inside the metals (Al, Brass, Cu and SS-304). The acoustic measurements were carried out using a calibrated microphone, (Ahuja, ATP-20, 50 Hz to 16 kHz). While the vibrations induced within the material before getting converted into ASW in the atmosphere are measured using vibration transducers (piezoelectric accelerometer). The arrival time of the vibration transducer was used to measure the particle velocity within the material that increased with increasing laser energy. The measurement of the arrival time of the ASW as a function of the microphone distance from the source of explosion was carried out. The shock velocity with respect to distance from the source of explosion followed an exponential decay. The arrival time of the ASWs was found to be increasing with the distance and independent of the incident light polarization. The shock arrival time with respect to incident laser energy showed an exponential decay where as the shock wave pressure and velocity were found to be linearly increasing with the incident laser energy. Overall acoustic energy has increased with increasing density of the material. Evolution of different frequencies of the ASWs and the Vibrations will be presented.

References

1. M.S. Schneider, B. Kad, D.H. Kalantar, B.A. Remington, E. Kenik, H. Jarmakani, M.A. Meyersem, International Journal of Impact Engineering

32, 473-507 (2005).

2. Y. F. Lu, M. H. Hong, S. J. Chua, B. S. Teo and T. S. Low, J. Appl. Phys.79, 2186 (1996).

3. Q. Qin, K. Attenbourough, Applied Acoustics 65, 325 (2004)

8433-70, Poster Session

Simulations of two types of crystals utilized as laser materials

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A simulation of melilite group of crystals as laser materials is done. The results of a previous, rigurous analytical study we have performed are used [1]. Two materials from the melilite group of crystals will be studied: akermanite Ca2Mg(Si2O7) and gehlenite Ca2Al(AlSiO7). These materials have been synthesized. Synthetic melilites have several applications; an example is pure SrLaGa3O7, as a substrate for epitaxal high temperature superconducting layers [2-4]. Several minerals with the melilite structure have been synthesized as potential laser materials. Typical melilite lasers are: SrGdGa3O7: SGGM and SrLaGa3O7: SLGM. Dopants can be Nd 3+, Eu3+, Cr3+, Er3+ and Pr3+. The broadband luminescence is increased by the disordered distribution of the dopant in the tetrahedra. Nd-doped SrLaGa307 crystals are used for their optical and generation properties in lasers. Laser performances of SLG melilite have been measured in a direction perpendicular to the optic c-axis [1,4]. In this direction Nd-doped SLGM laser rods have output energies twice as much as Nd-doped YAG, (Yttrium Aluminium Garnet) laser rods. Therefore Pracka [5] suggested the use of Nd-doped SLGM in high energy requiring systems, by example for surgery, stomatology or laser marking.

In the paper the Crystal Morphology applied to lasers will be studied. The pulse energy of melilite single crystals perpendicular to the optical c-axis is relatively high. The cavity shape of the crystal determines also pulse energies. Therefore crystals elongated by the c-axis are needed. In this respect only hydrothermal akermanite crystals have long dimensions, but these crystals are far too small and might contain impurities, such as hydroxyl ions. The {001} faces of melilite crystals are used as a substrate for epitaxial high temperature superconducting layers [5]. Theoretical growth form of sample has large {001} faces but a method has to be found to obtain single crystals.

[1] Nicolov, MF, Calculated growth form of melilites, Zeitschrift fur Kristallographie, 219(10),(2004) pp. 630-636.

[2] Gilbert T.L., Soft -Sphere Model for Closed -Shell Atoms and Ions, J. Chem. Phys. 49 (1968) 2640-2642

[3] Pajaczowska A., Gloubokov A., Klos A., Woensdregt C.F., Czochralski growth of SrLaAlO4 and SrLaGaO4 single crystals and its implications for the crystal morphology, J. Crystal Growth, 171(1997) 387-391.

[4] Woensdregt C.F., Janssen H.W.M., Gloubokov A., Pajaczkowska A.,Growth morphology of tetragonal ABCO4 compounds : theory and observations on Czochralski grown crystals, J. Crystal Growth, 171 (1997)392-400.

[5] Pracka I., Giersz W., Swiekowicz, Pajaczkowska A., Kaczmarek S, Mierczyk Z., Kopczynski K., The Czochralski growth of SrLaGa3O7 single crystals and their optical and lasing properties , Materials Science and Engineering B26 (1994)201-206.

8433-71, Poster Session

Stability analysis of solid-state lasers regarding thermal lensing effect

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The stability of solid-state lasers is influenced by the thermal lensing effect in the crystal. This effect is based on the deformation of the end faces of the crystal and the temperature dependence of the refraction index. It also depends on the photoelastic effect produced by thermal induced stress in the crystal.

The analysis of the photoelastic effect is important for high power lasers and for lasers with a radially polarized laser beam. In this work, we use FE model to calculate the deformation, heat and stress distribution in the laser crystal with high accuracy. We also simulated the refraction index anisotropy with respect to the crystal orientation using the calculated stress distribution. As a result of our simulation, we can study stability of laser resonators for both radially and azimuthally polarized laser beam.

8433-73, Poster Session

Photodarkening measurements in Yb: doped silica fibers

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In this study, detailed investigation of photodarkening in Yb - doped silica fibers is reported. The cooperative luminescence loss influenced by photodarkening is measured simultaneously with 633 nm probe loss. The results indicated lower cooperative luminescence loss at 513 nm than expected. The following set of measurements described bleaching processes caused by 633 nm laser light source.

8433-11, Session 3

Current confinement in EP-VECSELs for high power single mode operation suitable for passive mode-locking

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Vertical External-Cavity Surface-Emitting Lasers (VECSELs) can be used for passive mode-locking, and allow mass production and integrability with Semiconductor Saturable Absorber Mirrors (SESAMs) due to their semiconductor nature. In addition ultra short pulses can be generated due to their low dispersion in comparison to EELs. Electrically pumped (EP-) VECSELs have the additional benefit of a compact design since they don't need a setting for the optical pumping, but the features of power scalability and a fundamental TEM00 mode present in optically pumped VECSELs are still challenges that need to be overcome.

We use a detailed physical model to perform electro-opto-thermal coupled simulations of EP-VECSELs, to optimize their design towards high power CW single mode operation as a prerequsite for mode-locking. The design and fabrication of those devices has been published earlier, and we were able to show a good agreement between simulation and measurement results [1]. The design aimed to achieve an optimal current injection into the center of the devices to maintain a fundamental mode operation under all operating currents. This is achieved by using a small radius circular contact at the bottom of a p-doped DBR for hole injection. This makes use of the low hole mobility, and thus their strong confinement to the center before reaching the active region. In addition we use a current spreading layer for electrons injected from the ring top contact which can spread more effectively towards the center of the device due to their high mobility. Despite the optimized design with a maximum output power of 120mW, the simulations of those devices show a less than optimal current injection profile for both electrons and holes in large diameter devices (starting at 150um radius top contact with 40um radius bottom contact), in addition to a significant leakage current.

The holes injected at the bottom contact spread out towards the negative ring contacts which causes a diminishing supply of charges to the center and an increased injection at the edge of the bottom contact. This causes

a strong current leakage and leads to a doughnut shaped carrier profile in the quantum wells forming a dip in the center. As a consequence it leads to a smaller gain for the fundamental mode and an increased gain for higher modes. The stimulated emission also amplifies this effect through spatial hole burning.

To solve this problem, different strategies are pursued in this work. One is to introduce a mesa etch around the bottom contact to prevent the holes from spreading outwards, thereby reducing the leakage current and increasing the carrier density in the center. This leads to a Gaussian shaped gain profile, and an increased gain for the fundamental mode. With this design we are able to reach an improvement of 20% in maximum output power and counteract the spatial hole burning effect in those devices. Additionally, this design enables a better cooling of the device with proper heat sinking. We also investigate strategies to enhance the electron injection towards the center of the device, e.g. by adding an oxide confinement or doping gradients beneath the top contact.

References:

1- Electrically Pumped Vertical External Cavity Surface Emitting Lasers Suitable for Passive Modelocking, Yohan Barbarin et.al. IEEE Journal of Selected Topics in Quantum Electronics, Volume: PP Issue: 99.

8433-12, Session 3

Femtosecond Cr:colquiriite lasers pumped by high-brightness red tapered diodes

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Ti:Sapphire lasers have the broadest gain bandwidth among all solid-state laser materials and could provide tunable femtosecond pulses in the 680-1180 nm region. However, due to the requirement of expensive green pump sources, the current cost of Ti:Sapphire laser technology sets a barrier to its widespread adoption. As an alternative, Cr :Colquiriites (Cr:LiCAF, Cr:LiSAF, Cr:LiSGaF) also possess broad gain bandwidths and their total cw tuning range cover the 720-1110 nm region. The main advantage of Cr :Colquiriites is their broad absorption bands around 650 nm which enable direct diode pumping by low-cost red laser diodes. However, so far the limited brightness of red diodes required combination of four to six pump diodes to reach reasonable output power levels from Cr :Colquiriites. This complex pumping geometry increases cost and causes stability issues in long-term operation. In this study, we report low-cost and efficient Cr:Colquiriite lasers that are pumped by recently available high-brightness tapered diode lasers (TDLs). Upon pumping the Cr:Colquiriite lasers with two 1-W TDLs, we have demonstrated output powers of 850 mW and 650 mW together with slope efficiencies of 49% and 42% from continuous-wave (cw) Cr:LiSAF and Cr:LiCAF lasers, respectively. In cw mode-locked operation, using different cavity configurations, 50 to 250 fs long pulses with average powers of 200-450 mW were obtained at repetition rates around 80 MHz. The corresponding pulse energies were 2.5 to 5.5 nJ, which are the highest energy levels reported so far at these repetition rates. Our findings indicate that TDLs in the red spectral region are likely to become the standard pump source for Cr:Colquiriite lasers in the near future. Moreover, these TDL pumped, compact Cr:Colquiriite systems represent an attractive low-cost alternative to Ti :Sapphire technology and bear the potential to significantly accelerate research based on cw and femtosecond lasers in this spectral region.

8433-13, Session 3

Dispersion management with a normal dispersive fiber in an ultrafast thulium-doped fiber laser

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We present an ultrafast thulium-doped fiber laser with an intracavity fiber based dispersion management and external compression by a normal dispersive fiber. To achieve mode-locked operation by using nonlinear polarization rotation, two pairs of half wave and quarter wave plates were implemented in the free space section before and after the isolator. The active part of the unidirectional ring laser consisted of 0.7 m thulium-doped fiber which was pumped by an Erbium-laser via a 1575 nm/1980 nm wavelength division multiplexer. To adapt the mode field diameters of the out- and incoupling of the free space section, two pieces of 0.3 m of SMF28 were spliced to both ends of the fiber section.

For dispersion management, 2.20 m of normal dispersive fiber, which had a very high NA of 0.28 and a small core diameter of 2.72 µm, was implemented into the resonator. The normal dispersion of the fiber at a wavelength of 1910 nm was estimated to +0.044 ps^2/m, resulting in an overall dispersion of the laser of -0.01 ps^2.

Self-starting of mode-locked operation was achieved at a pump power of 187 mW. Due to generation of multiple pulses, the pump power had to be reduced to 55 mW to obtain single pulse operation with an average output power of 7.8 mW. This corresponds to a pulse energy of 170 pJ with a repetition rate of 45.43 MHz. The spectrum of the pulses spanned from 1800 nm to 1975 nm and contained sidebands on the longer wavelength part. The pulses had a peak wavelength of 1912 nm and a spectral full width at half maximum (FWHM) of 32.5 nm. The overall spectrum was covered with sharp dips, generated by the absorption of water molecules.

The uncompressed pulses of the oscillator were slightly negative chirped and had an autocorrelation FWHM of 698 fs. The pulses were externally compressed using 0.55 m of the same normal dispersive fiber, which was also used inside the cavity. After compression, an autocorrelation FWHM of 184 fs was achieved. With an assumed Gaussian shape, this corresponds to a pulse duration of 130 fs (squared hyperbolic secant shape: 120 fs respectively). The provided dispersion of the external compressor fiber was estimated to +0.0242 ps^2. Due to uncompressed dispersion of higher orders, the measured autocorrelation trace had a broader pedestal which could not be compressed by the normal dispersive fiber. Another reason for this could be a complex dispersion structure caused by the absorption of water molecules inside the laser cavity. Purging with nitrogen or argon might reduce this effect.

First simulations of the laser system with the above mentioned parameters showed a good agreement to the experiment. Further investigation might outline critical parameters of the ultrafast laser system and give insight into pulse evolution inside the laser cavity.

8433-14, Session 3

Efficient high-power narrow-linewidth all-fibred linearly polarized ytterbium laser source

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In this paper, we report theoretical and experimental results on a high power, all-fibred, linearly polarized, picosecond laser source based on Ytterbium (Yb) Large Mode Area (LMA) doped fibres. The architecture of the laser is based on a Master Oscillator Power Amplifier (MOPA), namely a mode-locked fibre laser oscillator followed by two amplification stages. The oscillator is based on linearly polarized single mode Fabry-Perot cavity. Self starting is ensured by using a SEmiconductor Saturable Absorber Mirror (SESAM) at one end of the laser cavity. The other mirror of the cavity is a narrow Fibre Bragg Grating (FBG) that contributes to the mode-lock regime and the generation of ultrashort pulses. We obtain a stable mode-locking regime centred at 1030nm, with pulse duration of 5ps and spectral linewidth of 0.3nm. The repetition rate of the laser is fixed to 50MHz. The pulse width of the oscillator is then stretched to 40ps with a chirped fibre Bragg grating. The stretching induces a negative chirp to the pulses. These pulses are then amplified by a first polarisation maintaining single mode amplification stage to 100mW. With this 6µm core diameter amplifier, no non-linear effects are identified up to this power level. A second amplification stage is used to reach 25Watts. This last booster stage is based on a commercially available step index LMA fibre with a core diameter of 20µm, and a numerical aperture of 0.06. With an optimum use of Self Phase Modulation (SPM) during amplification, the spectral linewidth of 0.3nm remains at 25W, making this laser an ideal candidate for subsequent wavelength conversion processes. The efficiency of the high power amplification stage is 50%, without significant temporal and spectral distortion. This all-fibred linearly polarized laser is a good candidate for various applications, in particular where short pulse, high power and narrow linewidth are required.

8433-15, Session 4

Optically induced switching between mode-locked and unmode-locked continuous wave regimes of a femtosecond Cr:forsterite laser

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The ability to control the temporal output from a femtosecond laser can enable the same laser to be used for multiple functions, for example, the laser used in an optical tweezers system could be used as a constant-intensity source to trap a biological cell and then be temporarily switched to mode-locked operation to effect photoporation. Here, we report the rapid switching of a Cr4+:forsterite laser between mode locked and unmode-locked continuous wave regimes via the optical pumping of an intracavity SESAM element. Mode locking of the laser was initiated by an intracavity quantum well (GaInAsN) SESAM having an anti-resonant design (delta R ~0.3%, photoluminescence peak ~1310nm) that yielded transform-limited 89fs pulses centred around 1295nm with a repetition rate of 162MHz and an average power of 64mW. Upon excitation of the SESAM with 600mW of extra-cavity power from an 808nm semiconductor diode laser, switching could be induced between the unmode-locked and mode-locked regimes. Transitions free of Q-switching or relaxation oscillations were observed with <200µs switching times for both for the initiation and cessation of mode locking. Periods of mode locked operation of custom duration could be produced by appropriate control of the SESAM pump diode enabling the generation of bursts of pulses as short as 400µs. Switching was confirmed to originate from local pump-induced heating of the SESAM by observing the laser going through identical regime switching when the chip temperature of the 'unpumped' SESAM was raised by ~25°C.

8433-16, Session 4

Mode-locked femtosecond all PM Yb fiber laser delivering linearly chirped pulses

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Mode-locked fiber lasers have many advantages including high efficiency together with simplicity stability and compactness. As a result these lasers are now finding many applications. The physics of mode-locked fibre lasers relies on a complex interaction between the gain, the nonlinear effects and the dispersion leading to quite different modes of operation in the normal and the anomalous dispersion regimes. In the recent years an increase in the energy delivered by fibre laser as been made possible by operating in all-normal dispersion (ANDi) cavities [1,2]. The nonlinear pulse evolution in an ANDi lasers ensures that the pulse accumulates a positive chirp and steadily increasing pulse duration and energy during cavity amplification. These high quality, high energy pulses can be efficiently compressed to femtosecond durations.

We report on the generation of linearly chirped pulses from a self-starting, all polarization maintaining fibre laser which has no dispersion compensation elements. Mode-locked operation is generated by a Nonlinear Amplifier Loop Mirror (NALM). This environmentally stable 10MHz laser delivers linearly chirped 7.6 ps pulses which could be externally compressed to 344 fs. The average power of the output pulses is 3mW corresponding to a peak power approaching a kilowatt.

An interesting feature here is the absence of a saturable absorber mirror (SAM) to ensure the mode-locking operation. SAMs have been widely used recently to improve the performances of fibre lasers [3] and to ensure mode locked operation in the absence of diepersion compensation. They suffer nonetheless, from inevitable degradation over time which limits their commercial application. The use of robust components such as those in a NALM allows the development of robust, long lifetime systems.

A second important feature of our laser lies in its repetition rate, which is lower than that of most other other all normal dispersion fibre lasers, and in the availability of a picosecond chirped pulse output, enabling the laser to be used as the front end of a CPA system having reduced complexity.

[1] A. Chong, J. Buckley, W. Renninger, and F. Wise, Opt. Express 14, 10095(2006).

[2] F. W. Wise, A. Chong, and W. H. Renninger, Laser & Photon. Rev. 2, 58(2008).

[3] B. Ortaç, M. Plötner, J. Limpert, and A. Tünnermann, Opt. Express 15 16794(2007).

8433-17, Session 4

Positively chirped pulses from a mode-locked thulium fiber laser

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We report on positively chirped pulse operation of a single-mode thulium-doped fiber laser. The laser was set up in a ring resonator configuration. It was hybridly mode-locked via nonlinear polarization evolution and a semiconductor saturable absorber mirror, which was implemented into the resonator in a sigma-arm configuration. The 0.9 m long active fiber was core-pumped via a WDM at 1574 nm. Dispersion management was implemented via a small core, high NA fiber, providing normal dispersion up to a wavelength of more than 2 µm due to considerable waveguide dispersion. The resulting overall cavity dispersion with 0.04 ps^2 at 1930 nm, determined by measuring the frequency-dependent group delay, was slightly normal.

Single pulse operation was reached at about 150 mW of launched pump power. The average output power was 13 mW, corresponding 0.7 nJ pulse energy at the fundamental repetition rate of 19.7 MHz.

At -10 dB, the optical spectrum extended from 1917 nm to 1941 nm with two peaks, a structured, but flat top and very steep edges, which are characteristic for positively chirped pulse operation.

The pulses directly delivered from the laser were significantly chirped. The full width at half maximum of the autocorrelation trace was about 12 ps. With a standard grating compressor providing -1.04 ps² dispersion, the pulses could be compressed to 482 fs duration, which was 13 % above Fourier-limit.

According to the dispersion provided for pulse compression, the pulses were positively chirped during the entire resonator roundtrip. Therefore, the laser operated in a positively chirped pulse regime, similar to the similariton regime, which has previously been demonstrated with Ytterbium and Erbium fiber lasers.

Although the laser operates in a positively chirped pulse scheme, the pulse energy appears to be limited by accumulation of nonlinear phase. If the pump power was increased above 150 mW, broadening of the optical spectrum was accompanied by an increasing FWHM of the AC trace after compression. This larger AC FWHM could not be balanced by readjustment of the grating distance and hence indicates a more nonlinear chirp. Consequently, with further increase of pump power the mode-locked operation became unstable, revealed by an irregular pulse train and sidebands in the radio-frequency spectrum.

The experimentally observed results could well be reproduced by numerical simulations, which give further insight into the evolution of the pulse parameters during the resonator propagation and the respective limitations. Therefore, they provide an ideal tool for further optimization of the laser cavity to adapt the output pulse parameters.

8433-18, Session 4

Using graphite nanoparticle doped thin PVA film as saturable absorber for passively mode-locking erbium-doped fiber ring laser

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Nano-scale semiconductor based saturable absorber as the mode locker has played a key role in the passively mode-locked fiber lasers recently. The typical saturable absorbers such as semiconductor saturable absorber mirror (SESAMs) and carbon nanotube (CNT) are replaced by graphene, which have the advantages of broadband operation, tunable saturable loss, fast recovery time and fabrication flexibility. In contrast to current approaches, the graphite nano-particles which exfoliated and polished from a graphite foil are preliminary utilized as the saturable absorber to generate soliton mode-locked Erbium (Er) doped fiber ring laser. After mixing the graphite bulk into nano particles in PVA solution and brushing them directly on the single-mode fiber (APC) end-face, a fiber ring laser can be generated with ultrashort pulse.

Raman scattering spectrum of the graphite nano-particle doped PVA film reveals two distinct peaks of G band at 1580 cm-1 and D band at 1260 cm-1. The small intensity ratio (ID/IG) of D band (ID) and G band (IG) indicates highly crystalline graphite. The modulation depth of the saturable absorption for graphite nano particles is 20% with increasing average power from 5 to 100 mW under a sub-ps pulse laser excitation. The ring laser loop includes an Er-doped fiber amplifier (EDFA) as the gain medium, a polarization controller and a 1X2 coupler (90/10), which provides 90% feedback and 10% output. The graphite bulk is milled into nano particles and detected by SEM. These nano particles are directly brushed on the fiber end-face and connect with another patch cord by adapter. This novel approach can generate soliton mode-locking laser with pulse width of 482 fs under saturable absorber coverage ratio of 25%. The central wavelength is located at 1564 nm with FWHM of 2.87 nm. The frequency spacing of first-order Kelly sideband (ν) is 0.69 THz from the central wavelength peak.

8433-19, Session 5

Top-hat beam output from a large mode area microstructured fiber for beam delivery

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Fiber technology has a great potential to improve the compactness and stability of laser systems. Recent progresses in fiber laser technologies have proven their capability to deliver high-power pulses suitable for many applications especially for industrial needs (laser marking, welding, cutting, drilling and heat treatment) or for laser-biological tissues interactions inside the body. Currently, the intensity profile at the output of a beam delivery single-mode fiber system exhibits a Gaussian-like structure. As a result, the intensity deposited on the target (material or biological tissue) is not uniform and the treatment leads to irregularity. The Gaussian profile must then be transformed to exhibit a 'top-hat' intensity profile. To avoid the use of complex beam shaping optics, an elegant and efficient solution is to achieve all-fibered system which directly delivers this desired beam profile. Highly multimode fibers represent the usual way to homogenize the field distribution. However they exhibit very low depth of focus that is detrimental for many applications.

In this talk, we will experimentally demonstrate that it is possible to simultaneously obtain 'top-hat' profile and high depth of focus by using a large mode area microstructured optical fiber whose refractive index profile flatten the intensity distribution of the fundamental mode. This is made possible by inserting a raised index ring around the central core. We will present properties of the fiber and recent experiments performed at 1 µm (like coupling efficiency, bent sensitivity, propagation losses, damage threshold, modal characterisation ...) demonstrating the feasibility of all-fibered top-hat beam delivery systems.

8433-20, Session 5

Applying refractive beam shapers in techniques of beam combining with using volume Bragg gratings

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The technique of spectral combining the laser beams with using volume Bragg gratings operating as narrow band spectral mirrors allows to reach extremely high resulting power through combining the radiation of several powerful lasers. Performance of these volume Bragg gratings in terms of reflectivity, stability of spectral characteristics depends on their temperature, especially on the temperature profile being a result of interaction of the incident or passing through radiation of powerful laser with material of the grating. Most of effects appear as result of energy absorption the temperature profile corresponds to the intensity profile of a laser beam applied, the Gaussian intensity distribution leads to higher temperature in the central part of a grating and, hence, changing its operating specifications. Homogenizing of the temperature profile over the working field of a volume Bragg grating would increase efficiency of its operation. This can be realized through applying the beam shaping optics, for example refractive field mapping beam shapers providing high flexibility in building various optical setups due to their unique features: almost lossless intensity profile transformation, providing flattop, supergauss or inverse Gauss profiles with the same beam shaper, saving of the beam consistency, high transmittance and flatness of output beam profile, extended depth of field, capability to adapt to real intensity profiles of TEM00 and multimode laser sources. Combining of the refractive field mapping beam shapers with other optical components, like beam-expanders, relay imaging lenses, anamorphic optics makes it possible to generate the laser spots of necessary shape, size and intensity distribution.

This paper will describe some design basics of refractive beam shapers of the field mapping type, with emphasis on the features important for building and applications of high-power laser sources. There will be presented results of applying the refractive beam shapers in real research installations.

8433-21, Session 5

Low speckle line generation using a semiconductor laser source

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Line generators are laser based devices that are currently used worldwide in automated process control and inspection systems. The accuracy of this type of measurement, which is based on taking an image of an object illuminated by the laser line, depends on the accuracy with which the middle of the projected line can be determined. Therefore when using a coherent laser light source, inevitably the measurement process will be distorted by an interference phenomenon called speckle. Speckle, which shows up as noise or granularity in the recorded image, occurs whenever a rough surface is illuminated by a coherent light source, causing random light intensity variations. Speckle clearly limits the resolution of measuring systems based on optical line generators. Thus reducing the amount of speckle is important in order to increase the measurement resolution. Several methods already exist in order to reduce speckle in laser illumination and projection applications, almost all based on averaging out the effect, e.g. by having the laser beam pass through a rotating diffuser. In this contribution however we intend to show that we can also design a low speckle line generator based on the reduced spatial coherence of a broad-area vertical-cavity surface-emitting laser (BA-VCSEL). This type of semiconductor laser can be driven into a special operation regime, a regime of low spatial coherence, which has already been shown to have a speckle reducing effect for image projection applications. However, the effectiveness of reducing speckle strongly depends on the line generating optics. Therefore we compare different line generating optical systems on their potential to use spatially incoherent laser emission for speckle reduction. Our line generator setup consists of a VCSEL laser source, a line generating optical component, a paper screen on which the line is projected, and a ccd camera to capture the line. A set of relay lenses is used in order to first collimate the laser beam on the line generator, and then focus the line on the screen.

With this setup we are able to characterize the amount of speckle, using one of the following line generator systems: a single cylindrical lens, a tandem cylindrical lens array or a diffuser based line generator. We also compare these results with the speckle occurring if we replace the partial spatially coherent VCSEL with a single mode laser or with a multi-mode VCSEL. We draw conclusions on the design of the most optimal optical system. The results of our study are also valid for other sources of partial spatially coherent emission.

8433-22, Session 5

Beam shaping in high-power laser systems with using refractive beam shapers

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Beam Shaping of the spatial (transverse) profile of laser beams is highly desirable by building optical systems of high-power lasers as well in various applications with these lasers. Pumping of the crystals of Ti:Sapphire lasers by the laser radiation with uniform (flattop) intensity profile improves performance of these ultrashort pulse high-power lasers in terms of achievable efficiency, peak-power and stability, output beam profile. Specifications of the solid-state lasers built according to MOPA configuration can be also improved when radiation of the master oscillator is homogenized and then is amplified by the power amplifier. Features of building these high power lasers require that a beam shaping solution should be capable to work with single mode and multimode beams, provide flattop and supergauss intensity distributions, the consistency and divergence of a beam after the intensity re-distribution should be saved and low absorption provided. These specific conditions are perfectly fulfilled by the refractive field mapping beam shapers due to their unique features: almost lossless intensity profile transformation, low output divergence, high transmittance and flatness of output beam profile, extended depth of field, adaptability to real intensity profiles of TEM00 and multimode laser sources. Combining of the refractive field mapping beam shapers with other optical components, like beam-expanders, relay imaging lenses, anamorphic optics makes it possible to generate the laser spots of necessary shape, size and intensity distribution. There are plenty of applications of high-power lasers where beam shaping bring benefits: irradiating photocathode of Free Electron Lasers (FEL), material ablation, micromachining, annealing in display making techniques, cladding, heat treating and others.

This paper will describe some design basics of refractive beam shapers of the field mapping type, with emphasis on the features important for building and applications of high-power laser sources. There will be presented results of applying the refractive beam shapers in real installations.

8433-23, Session 6

Laser materials processing

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No abstract available

8433-24, Session 6

Development of a laser based process chain for manufacturing freeform optics

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The current state of development of a laser based process chain for manufacturing fused silica optics is presented. The process chain consists of three laser based process steps in a modular design so that they can be included in conventional manufacturing processes as well. The high speed laser ablation as the first process step forms the optics' surface by locally removing glass material through ablation in a short time independently of the desired surface shape. The second process step reduces the induced surface roughness by remelting the surface without removing any material. The high precision laser ablation as the third process step ablates eventually remaining redundant material to further reduce the surface roughness. For the polishing process, a CO_2-laser is compulsory, whereas the ablation steps can also be carried out by using an ultra-short-pulse (USP) laser. Current results show an ablation rate > 20 mm³/s with a resulting surface roughness Ra < 3 µm for the high speed ablation and a minimal ablation depth of < 5 nm per layer for the high precision laser ablation (both using CO_2 laser radiation). With the use of an USP laser and its ablation without temperature induction, different materials can be processed and the spatial resolution can be increased due to its smaller focus diameter. The polishing process already reaches values that are sufficient for lighting optics (Rq = 3 nm, Wq = 8 nm, PV = 4 µm, micro roughness = 0,32 nm) with an area rate ≈ 1 cm²/s. Although the process steps are investigated separately, a first combination already showed promising results. In addition to the optimization of each process step, suited conjunction points between the steps will be investigated in the future.

8433-25, Session 6

Laser processing of GaN-based LEDs with ultraviolet picosecond laser pulses

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Picosecond (ps) lasers provide a universal tool for material processing. Due to the short laser pulse length material is removed by a process called “cold ablation”, with minimal thermal damage to neighbouring regions. As a result, better defined structures with smother and cleaner side walls can be fabricated than with “long-pulse” lasers. This offers new possibilities for laser processing in semiconductor technology for both semiconductor materials and contact or bond metallization.

The fabrication of optoelectronic devices such as LEDs typically requires photolithography steps, requiring specific lithography masks be fabricated which, in particular for prototyping, is expensive and time consuming. Therefore one would like to replace these steps by direct writing techniques such as laser processing, which will speed up the development and prototyping of new devices.

In this presentation we report on fully laser processed planar GaN-based LEDs fabricated without any photolithography steps. On the bare semiconductor isolation trenches and mesa structures are formed directly by ultraviolet ps laser pulses. In the former case, the grown epitaxial layers have to be cut through completely. Due to the large difference in ablation threshold between the substrate material and the epitaxial layers a broad range of processing parameters is available. In contrast, the process to realize mesa structures is more critical as smooth sidewalls with low surface leakage currents are required. Therefore the focus diameter as well as other laser parameters such as inter-pulse distance and pulse energy plays an important role in realizing structures which fulfil the above criteria. For the direct deposition of patterned ohmic contact and bond metallizations, the ps laser fabrication and subsequent use of high resolution shadow masks is presented, which exhibit a significantly reduced sidewall roughness compared to masks produced by ns laser pulses. Due to the higher precision of the laser defined structures it becomes possible to deposit multiple layers, by evaporation through shadow masks, on top of each other through the use of alignment marks, similar to multiple mask level photolithography.

Finally, the ps laser processed LEDs are electrically and optically characterized and their characteristic compared with that of conventionally fabricated mesa LEDs.

8433-26, Session 6

Investigations of the temperature regimes of the selective laser melting

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For the precision control of the SLS/SLM processes the measurements of the main parameters of these processes - maximum surface temperature , temperature distribution in the processing area , size of the melt and control their evolution are necessary [1].

The most-used galvo scanner systems have a selective character of reflection depending of wavelength and angle of rotation , that must be take in account in deciding on a spectral range of temperature measurements. Also custom made F- teta lens are not achromatic usually. That causes image shift in coaxial set-up sensor positioning systems between the laser focus spot and its image at a wavelength different from the laser one.

The principles of measuring the surface temperature of powder bed in the focal spot of the laser radiation while scanning the surface using galvoscanner with F-teta lens have been designed [2]. The optical system devised [3] provides the possibility to measure spatial distribution of brightness temperature and selected temperature profiles, measurements of maximum brightness and colour temperature in the laser focal spot.

Investigation of the melting of the overhang layers has been conducted under full temperature monitoring . The mechanisms of the melt penetration into loose powder bed have been determined:

Accumulation of heat in the molten overhange layer results in the development of the instability of the contact surface between the melt and loose powder in a gravity field - Rayleigh - Taylor (RT) instability. RT instability progress under laser radiation action causes the complete loss of stability of the molten layer with a dip to the loose powder bed.

The second mechanism of super-deep penetration of laser radiation in a powder bed has associated with balling effect. Large drops of melt draw nearby powder with resulting laser radiation penetration to a depth up to 2-3 mm.

In either case the destruction of layer is associated with a overheating and after a lapse of time the process passes to steady state with surface temperature 1500 K for Cu powder because the previously melted material act as a heat sink.

1. Chivel Yu., Smurov I. Temperature monitoring and overhang layers problem. Physics Procedia .V.12, p. 712 (2011).

2. Chivel Yu. Method and device for measuring the surface brightness and colour temperature in the area of the laser irradiation. Patent Application 2010107443, (2010).

3. Chivel Yu. Device for temperature measurements Patent Application 2011235186 (2011)

8433-27, Session 6

Monitoring of the protective glass during laser cladding with active fiber laser

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The paper deals with the monitoring of the protective glass in a laser cladding head specifically designed for high power active fiber laser beams. The available high power density that can be focused on the workpiece surface is not only one of the most well known positive features of the fiber laser sources but becomes a very critical thermal load acting on the optical elements of the laser cladding head, in particular in dirty processes such as the laser cladding. The cladding powder indeed coming from the powder cone is likely to interact with the optical elements of the cladding head. As a result the optical elements become locally opaque and absorb the laser beam, with consequent thermal deformation, coating damage and lens breakage. The protective glass, that divides the focusing and collimation lenses from the dirty work area, has the fundamental role to protect the entire optical chains and represents the element whose life has to be continuously monitored in order to avoid unexpected and unpleasant lens damages.

The paper presents the study of a monitoring device aimed at monitoring the life of the protective glass making use of two different signals. The first one is the scattered light from the protective glass, the second one is the temperature signal from the protective glass cartage. The developed monitoring device is extremely compact and is able to recognize both small (i.e. cracks) and big defects (i.e. diffuse opacity) on the surface of the protective glass. The monitoring device has been tested in several cladding experimentations, that have reproduced typical industrial cases in this filed: cladding of worn dies to be used in the plastic injection process, repairing cladding of turbine blades and anti-corrosion cladding of extrusion threads for injection machines.

This dense experimentation has allowed to test the monitoring device performance and has given significant insights to the definition of the monitoring strategies based on the proposed monitoring architecture.

In particular the most important results can be summarised as follows: i) the signal of the scattered light acquired during the period of fiber laser off, opportunely pre-amplified, is a valid indicator of the glass state; since is able to put in evidence both random events, such as the deposition of powder, and continuous coating damage, ii) the temperature signal is not as prompt and indicative of the glass life as the scattered light but can be indicative of the overall laser head heating, iii) the signal of the scattered light acquired during the fiber laser on is more complex and not so easy to be correlated to the glass condition.

8433-28, Session 6

Three-dimensional modeling of melting and crystallization during laser cladding process with coaxial powder injection

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Unsteady heat transfer with simultaneous melting and crystallization at laser cladding process with coaxial metal powder injection is investigated numerically. 3D model based on self-consistent nonlinear heat equations and kinetics of phase change. It accounts for melting evaporation, crystallization, evolution of free surface and powder injection. The main attention is devoted to investigation of nonlinear kinetics of phase change, modeled by Kolmogorov-Avraami equation. Free boundary of melt pool is tracked by level-set method. 3D temperature distributions in cladding track and phase distribution profiles were analyzed due to different parameters of laser radiation and particle flow. Results are compared with models based on empirical formulas for the phase change. Numerical modeling determined that the main parameters that govern melt pool dynamics and system maximum temperature are mass flow rate, powder injection velocity, laser power, and scanning speed. Also it is determined that taking in to account the kinetics of phase change results in melt pool boundary and melting temperature mismatch. This is due to the fact that melting occurs with certain superheating of solid phase and crystallization with certain undercooling of liquid. Dimensions of melted zone (depth, width, length), and cladding height are compared with known experimental data.

8433-29, Session 7

Laser transmission welding of ABS using a tailored high-power diode-laser optical fiber coupled system

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Laser transmission welding of polymers is a direct bonding technique which is already used in different industrial applications sectors such as automobile, microfluidic, electronic and biomedicine. This technique offers several advantages over conventional methods, especially when a local deposition of energy and minimum thermal distortions are required. This report presents a study of laser weldability of ABS (acrylonitrile/butadiene/styrene) filled with two different concentrations of carbon nanotubes (0.01% and 0.05% CNTs). These additives are used as infrared absorbing components in the laser welding process, affecting the thermal and optical properties of the material and, hence, the final quality of the weld seam.

A tailored laser system has been designed to obtain high quality weld seams with widths between 0.4 and 1.0mm. It consists of two diode laser bars (50W per bar) coupled into an optical fiber using a non-imaging solution: equalization of the beam quality factor (M2) in the slow and fast axes by a pair of micro step-mirrors. The beam quality factor has been analyzed at different laser powers with the aim to guarantee a coupling efficiency to the multimode optical fiber. The power scaling is carried out by means of multiplexing polarization technique. The analysis of energy balance and beam quality is performed in two linked steps: first by means ray tracing simulations (ZEMAX®) and second, by validation

Quality of the weld seams is analyzed in terms of the process parameters (welding speed, laser power and clamping pressure) by visual and optical microscope inspections. The optimum laser power range for three different welding speeds is determinate meanwhile the clamping pressure is held constant. Additionally, the corresponding mechanical shear tests were carried out to analyze the mechanical properties of the weld seams. This work provides a detailed study concerning the effect of the material microstructure and laser beam quality on the final weld formation and surface integrity.

8433-30, Session 7

Stabilization of laser welding processes by means of beam oscillation

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Welding with high-brightness laser beams suffers from increased sensitivity of both, the process itself and the laser beam shaping optics [1]. Laser beam oscillations create comparably large melt pool surfaces while maintaining the high laser beam brightness. Fast laser beam oscillation is known to be favorable for joining of dissimilar materials [2,3]. In our work we use such oscillations to stabilize high-quality laser welding processes.

Our experiments were performed with oscillation frequencies in the kHz range and a maximum amplitude of 100 µm at a focal spot diameter of 100 µm. Different types of beam motion patterns on the metal surface were used. The melt pool dynamics was studied by means of high speed video observations and the weld seam properties were analyzed with metallographic cross sections.

Comparison of the cross sections for different oscillation properties clearly showed that the welding depth is given by the static beam properties, i.e. high brightness, while the weld width is given by the oscillation amplitude. The width corresponds to the width which is obtained by a static, lower brightness beam that has parameters equal to the time averaged oscillating high-brightness beam. We denote the time averaged oscillating beam with the term “virtual lower quality beam”. It follows that in many cases the process efficiency given by the amount of melt is improved by oscillation.

High-speed videos show that motion patterns have to be chosen carefully in order to minimize unwanted effects such as e.g. melt ejection. However, the aim of the present investigations is to improve process stability, in particular to make the welding process less sensitive to focus shift. Therefore the results of welding with an oscillating laser beam in different focus positions are discussed with regard to process stabilization.

[1] Abt, F.; Hess, A.; Dausinger, F.: Temporal Behaviour of the Focal Shift of Beam Forming Optics for High Power Single Mode Lasers Paper #1302 in Proceedings of the 27th International Congress on Applications of Lasers and Electro-Optics (ICALEO 2008), California, USA (2008) 561-568.

[2] Gedicke, J.; Olowinsky, A.; Artal, J.; Gillner, A.: Influence of Temporal and Spatial Laser Power Modulation on Melt Pool Dynamics Paper #1502 in Proceedings of the 26th International Congress on Applications of Lasers and Electro-Optics (ICALEO 2007), Orlando, USA (2007) 816- 822.

[3] Kraetzsch, M.; Standfuss, J.; Klotzbach, A.; Kaspar, J.; Brenner, B.; Beyer, E.: Laser Beam Welding with High-Frequency Beam Oscillation: Welding of Dissimilar Materials with Brilliant Fiber Lasers in Proceedings of Lasers in Manufacturing (LiM 2011), Munich, Germany, Physics Procedia 12 (2011) 142-149.

8433-31, Session 7

Pyrometry diagnostic in laser cutting technology

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Using of optical sensors for on-line monitoring of the roughness of the cut edge in laser cutting technology was suggested in [1-2]. In [3] development of this method and adaptive control system for laser cutting was described.

The data of measurements with multi-channel two-color pyrometer of temporal fluctuations of temperature on the front of the laser cutting of sheet metal thickness of 3 mm, 6 mm and 10 mm are obtained. The multichannel pyrometer was used to measure temporal fluctuations of T* in the range of frequencies up to 16 kHz with relative temperature resolution of +/-0.05%. Measurements were carried out for several values of cutting speed, pressure, auxiliary gas (oxygen), using a CO2 laser power of 1500 watts radiation and Ytterbium Fiber Laser Power with 1800 watts. The relationship of temperature fluctuations above 3 kHz was proven with the deformation of the surface of the melt flow on cutting front. It is shown that in the case of cutting by CO2 laser RMS of temperature fluctuations is greater than 10 K in the range of sub-millimeter capillary waves, but the case of the cutting with Fiber Laser RMS of temperature fluctuations is a value less than 3 K. The boundary between capillary-wave turbulence and hydrodynamic turbulence is shown to pass in the region of 1.5 to 4.5 kHz depending on the material thickness. The spectrum of capillary waves in the case of Fiber-Laser cutting is formed under the effect of forced surface deformation at lower frequencies, in particular related to the auxiliary gas jets. It is shown, that thermo-capillary effect with capillary-wave turbulence generation can be observed in locations, where exposition of melt surface by CO2 laser intensity exceeds 1 MW/cm2. Thus, an additional mechanism for the anomalous absorption in the front of cutting can compensate the low absorption of the metal in the case of 10.6 µm laser in comparison with the absorption of the metal in the near infrared range. The results of calculation of the threshold of the formation of thermo-capillary waves will be presented in dependence on the wavelength of laser light. The estimation of range generated capillary waves will be presented. The local temperature gradient along the surface of the melt is also estimated on the basis of experimental data. In case of cutting by fiber laser the boundary between the turbulent motions on the surface of the melt and the region of capillary-wave turbulence was defined about 70...100 mkm and the temperature fluctuations were below +/-0.5 K in the range of capillary-wave turbulence

1. P. Sforza, V. Santacesaria, In: SPIE Proceedings “Laser Materials Processing: Industrial and Microelectronics Applications” 2207, pp. 836-847 (1994).

2. Heyn H., Decker I., Wohlfahrt H. , In: SPIE Proceedings «Laser Materials Processing: Industrial and Microelectronics Applications», 2207, pp.381-391 (1994)

3. J. R. Duflou1, E. Fallahi Sichani, J. De Keuster1, J.-P. Kruth , In: Proceedings of the 28th International Congress on Applications of Lasers and Electro-Optics, November 2-5, 2009 - Orlando, Fl, USA, 102, 527-536 (2010)

8433-32, Session 7

Optimum power consumption at high-quality laser-oxygen cutting

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At the present moment, fiber lasers have demonstrated their high effectiveness in the cutting of thin metal sheets. However, 2 laser is the best when the high-quality cutting of thick sheets is needed. This report presents the results of the experimental investigation of the interaction between energy and mechanical characteristics of the laser cut for thick sheets. The target is to optimize the energy consumptions in of the process of high-quality oxygen-assisted laser cutting of low-carbon steel. This task is especially urgent because the efficiency of the 2-laser is considerably lower than in the case of fiber or disc laser.

The energy balance is measured for the optimal cutting parameters. The cutting mode which results in the minimal surface roughness is optimal. Processing of substantial experimental material enabled to obtain dimensionless criteria governing the high quality of the cut. It is established that as the sheet thickness is 5...25 mm, the roughness is minimum under the condition of Pe = const, Pe is the Peclet number. At the optimum Peclet number of 0.5, the laser energy, energy of oxidation reaction and thermal conductivity losses per a unit of sheet thickness remain constant within the whole thickness range. Thermal efficiency and share of oxidized iron are also constant for various thicknesses as the roughness is minimal.

The obtained results permit to estimate the maximum thickness of the sheet on which the qualitative cutting can be done, as well as the laser power needed to do this cutting.

8433-33, Session 7

Regression modeling to predict the geometric characteristics of Ti6Al4V thin sheets butt joints welded by disk laser

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The high strength to weight ratio and good corrosion resistance of titanium alloys are two features which make them excellent for structural use especially in automotive, aerospace and medical applications. Increased reactivity with atmospheric elements at high temperatures of titanium alloys needs additional precautions to shield the molten weld pool in the welding process.

Welding is a fundamental process for the production of parts and always presents considerable problems. Laser welding is a high energy density process that offers more advantages (high welding speed, high penetration depth, narrow heat affected zones, slim beads, etc..) than traditional welding technologies.

The aim of this work is to investigate the effects of power, welding speed and defocusing on geometric characteristics and on defects of 1 mm Ti6Al4V laser welded butt joints by a new generation disk laser (TRUMPF Trudisk2002) with 2 kW of maximum power. The active gain is a Yb:YAG disk (thickness of 200 µm) instead of traditional Nd:YAG rods. Disk geometry allows to keep the nominal beam quality also at high power because there is no thermal lensing effect, typical of rod geometry. This laser has a focus diameter of 0.3 mm and a Rayleigh length of 2.8 mm. Laser beam generated by the source is delivered through fiber optics to the laser head, with a focal length of 200 mm, mounted on a robot IRB 2400 ABB six-axis that allows to create complex paths.

In a first exploratory investigation bead on plate tests (BoP) were done to estimate the range of laser parameters to be used and optimal values of the parameters related to the positioning of the nozzle and the shielding gas type and flow rate. The shielding system was composed of a nozzle, an upper diffuser and a lower diffuser onto which the plates were fixed.

A three level Box-Behnken experimental design with three repetitions is carried out for a total of 45 tests. Power values of 1400, 1600, 1800 W, welding speed values of 60, 80, 100 mm/s and defocusing values of -2, 0, +2 mm are chosen.

Linear and quadratic regression equations are developed to relate the input factors to the output variables in order to predict the geometric characteristics of butt joints.

8433-34, Session 7

Characterization of lap joints laser beam welding of thin AA 2024 sheets with Yb:YAG disk-laser

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Lap joints obtained by overlapping two plates are widely diffused in aerospace industry. Nevertheless, because of natural aging, adhesively bonded and riveted aircraft lap joints may be affected by cracks from rivets, voids or corrosion. Friction stir welding has been proposed as a valid alternative, although large heat affected zones are produced both in the top and the bottom plate due to the pin diameter. Interest has therefore been shown in studying laser lap welding as the laser beam has been proved to be competitive since it allows to concentrate the thermal input and increases productivity and quality.

Some challenges arise as a consequence of aluminum low absorptance and high thermal conductivity; furthermore, issues are due to metallurgical challenges such as both micro and macro porosity formation and softening in the fused zone.

Welding of AA 2024 thin sheets in a lap joint configuration is discussed in this paper: tests are carried out using a recently developed Trumpf TruDisk 2002 Yb:YAG disk-laser with high beam quality which allows to produce beads with low plates distortion and better penetration. The influence of the processing parameters is discussed considering the joint penetration and the fused zone. The porosity content as well as the metallographic features of the beads have been examined.

8433-35, Session 8

Biomedical optical imaging in the human retina using spectral scanning laser sources

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The technique of optical imaging using the laser light sources in medical sciences offers the potential for early diagnosis and effective therapies for variety of diseases. This technique has the ability to produce quick and non-invasive real time images at low intensity using light of definite wavelengths. The possibility to image using a number of different wavelengths simultaneously offers the potential for in vivo spectral imaging of the human tissue such as retina in order to reveal the early changes in tissue perfusion. This study reviews some potential scanning laser ophthalmoscope in retina imaging that has been undergoing of development in department of Biomedical Physics, at University of Aberdeen. We achieved a new spectral optical imaging technique using scanning laser ophthalmoscope which developed and adapted to detect early changes in tissue perfusion to indicate the starting of retinal disease in the eye. A summary of the technique and the results with healthy and retinopathy patients' eyes is presented.

The technique of spectral retinal perfusion imaging has many advantages over some previous approaches using fundus camera such as the high spatial resolution, fast imaging, low power laser light, less scattering and absorption light, simple combination of two wavelengths and no dye injection or eye drops. Retinal perfusion imaging has enabled us to study relative oxygen level in the fundus with a field of view of 25o. By illustrating the relative oxygen saturation level on the fundus image, the status of retinal circulation can be expressed as oxygen saturation levels, which cannot be done with fluoresce in angiography. There was good potential that angiography be replaced in some eye imaging fields by this method, to help diabetic retinopathy patients.

8433-36, Session 8

Holographic lithography for biomedical applications

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Holographic lithography (HL) is a powerful technique which allows fabrication of periodic microstructures over a large area by a single laser exposure. This technique is based on the recording of the interference pattern into a photosensitive material. HL technique is promising and attractive for mass fabrication of periodic structures due to several reasons: 1) minimal chemical postprocessing; 2) mask free; 3) does not require expensive and energy consuming high-vacuum or ultraclean environments; and 4) high productivity. By using this technique it is possible fast fabrication of different periodic structures such as pillars and microtubes arrays with different periods or more complex periodic microstructures like photonic crystals or C-shape structures. The form of fabricated periodic microstructures depends on phase, polarization and number of used laser beams. The period of fabricated periodic structures depends on wavelength of used laser and angle between interfering beams. The theoretical smallest period which can be fabricated by HL is equal half of used laser wavelength (diffraction limit), but practically the limit of the smallest period is larger than diffraction determined limit and it appears due to some limitations of the experimental setup.

Fabrication of suitable scaffolds with appropriate physical and mechanical characteristics is very important for successfully creation of tissue. Due to ability of fast fabrication of different periodic structures with different period, the HL technique is very suitable for scaffolds fabrication. The fabricated scaffolds by HL can be used in various biomedical investigations such as the cellular adhesion, proliferation and viability. These investigations allow select the suitable material and geometry of scaffolds which can be used in creation of tissue.

In this presentation we demonstrate possibilities of physical principles of holographic lithography technique, show examples of our fabricated periodic micro-structures and finally we discuss about possibility to use periodic microstructure for biomedical applications.

8433-37, Session 8

High-precision measurements of reflectance, transmittance, and scattering at 632.8 nm

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Precision instrumentation for measurements of reflectance, transmittance and scattering is important for the determination of the optical properties of materials and for the manufacturing of high-accuracy optical coatings. Since the introduction of an ion beam sputtering technique for the deposition of dielectric coatings, it became possible to manufacture ultra-low loss mirrors (with the absorption and the total integrated scattering less then a few tens of ppm) for use in lasers and electro-optical systems. In addition, there is at present considerable efforts and achievements in the areas of solar, nanostructures and microstructured coating materials, optical coatings degradation, laser-induced damage threshold determination, ultra-short pulse laser system coatings, etc.

Progresses in these fields require an increase in the sensitivity and accuracy of the optical characteristics measurement methods and systems. In this work we describe a high-accuracy system for measuring the main optical characteristics at 632.8 nm wavelength. The system comprises two methods: a laser ratiometric measurement method for absolute measurement of transmittance and specular reflectance, and an integrating-sphere method for assessment of the total integrated scattering. The system utilizes an intensity stabilized He-Ne laser as a light source. For further stabilization the output of the laser is divided into two beams by means of a beam splitter, where the first beam is sent to a monitor detector to normalize the laser power (which reduces the residual power fluctuations), and the second - to a sample surface for subsequent treatment. Two four-element trap detectors (S1337, Hamamtsu) are used: the first for monitoring of laser power, the second (fixed on a motorized stage) for the measurement of R and T, one after another. A PMT (R5900U-20, Hamamtsu) mounted to the exit port of a 40 cm diameter integrating hemisphere, is used for measuring of the total integrated scattering. To increase the dynamic range (more then 6 decades) of transmittance and absorption measurements special attention was given to the linearity measurements of the PMT and trap detectors. The dc signal from all detectors is simultaneously measured by means of three 6½ digit voltmeters for further data treatment by homemade software. A series of measurements with several reference mirrors showed that the system is able to measure the specular reflectance >99.995 % (repeatability <0.005% at 2 sigma), transmittance of 10-5 ppm with a repeatability <0.005% at 2 sigma, and total integrated scattering about 10 ppm (with a repeatability of <5 ppm at 2 sigma). We will also discuss the results of the influence of polarization state, environmental conditions, temperature, etc. on the measurement results, and long and short time stability of the system.

8433-38, Session 8

Airborne laser systems for atmospheric sounding in the near infrared

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This paper presents new techniques for atmospheric sounding using different laser sources, direct detection electro-optics systems and passive infrared imaging systems. The proposed techniques are suitable for both Earth remote sensing missions and likely future planetary exploration missions performed by using satellites, unmanned flight vehicles, gliders, balloons, roving surface vehicles, or permanent surface installations. The proposed techniques offer relative advantages and limitations in different scenarios. All are based on measurements of the laser energy (intensity and spatial distribution) incident on target surfaces of known geometric and reflective characteristics, by means of infrared detectors and/or infrared cameras calibrated for radiance. Various laser sources can be employed with wavelengths from the visible to the far infrared portions of the spectrum, allowing for data correlation and extended sensitivity. Errors affecting the measurements performed using the proposed methods are discussed in the paper and some algorithms are proposed that allow indirect determination of atmospheric chemical species and aerosol particles concentrations for Earth and other planets. These algorithms take into account a variety of linear and non-linear propagation effects. Finally, experimental results are presented relative to some test activities performed on Earth using the proposed techniques. Particularly, data are presented relative to both ground and flight trials performed with laser systems operating in the near infrared (NIR) at 1064 nm and 1550 nm. This includes ground tests performed with 10 Hz and 20 KHz PRF NIR laser systems in a large variety of atmospheric conditions, and flight trials performed with a 10 Hz airborne NIR laser system installed on a TORNADO aircraft, flying up to altitudes of 22,000 ft AGL.

8433-39, Session 8

Numerical simulation of a laser-acoustic landmine detection system

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The preliminary numerical simulation results obtained in the analysis of a landmine detection system based on laser excitation of acoustic - seismic waves in the soil and observing its surface vibration above the embedded landmine are presented. The presented numerical simulations comprise three main parts:

- Laser beam propagation and absorption in soil; a laser oscillator operated in Q-switched regime is considered; different laser wavelengths are investigated.

- Acoustic - seismic wave generation by absorption in soil of laser pulse energy;

- Evaluation of acoustic - seismic wave generation by the landmine buried in soil; comparison of Distributed Feed-Back Fiber Laser (DFB-FL) and Laser Doppler Vibrometer (LDV) detector used for soil vibrations evaluation.

The above mentioned numerical simulation are used for evaluation of an integrated portable detection system.

Several laser beam intensity transverse distributions, including multi-mode, Gaussian and top-hat, are investigated by numerical simulation in order to get information about soil laser energy absorption. The net result of this stage is a definition of acoustic - seismic vibrations generation in soil by absorption of laser pulse energy. In this sense several laser pulse time-shape are investigated.

Finite Element Method is used in order to investigate acoustic - seismic waves propagation in soil and how buried landmine becomes a secondary acoustic - seismic waves source.

Numerical simulations are used for performing a comparison between the Distributed Feed-Back Fiber Laser (DFB-FL) and Laser Doppler Vibrometer (LDV) detectors as potential devices used for construction of a laser-acoustic landmine detection system.

8433-72, Session 8

Three-dimensional Dip-in Laser Lithography (DiLL)

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In recent years, three-dimensional (3D) laser lithography has become a standard in 3D micro- and nanofabrication. Photosensitive material is exposed via two-photon polymerization by tightly focusing laser beam(s). Unfortunately, photoresists are commonly not perfectly index-matched to the oil immersion system and aberrations due to this mismatch lead to a dramatic loss of resolution and laser power with increasing writing depth.

To overcome this problem, we introduce Dip-in laser lithography (DiLL). In the DiLL process the objective lens is directly dipped into a liquid photoresist serving as immersion and photosensitive medium at the same time.

Using a dedicated DiLL setup, we proof the concept by fabricating a great variety of 3D structures. Heights in the millimeter range have been achieved with different commercial photoresists and with outstanding structural quality.

The focal intensity distribution is dependent on the refractive index of the photosensitive material. Theoretical calculations of the intensity distribution are presented for different configurations. Theory is in good agreement with the experiment.

For DiLL, the height of the structure is not limited by the working distance of the objective, i.e., high-NA objectives with short working distances can be used. Accordingly, best resolution is achieved independent on the writing depth or substrate.

8433-40, Session 9

Laser-plasma accelerators-based high-energy radiation femtochemistry and spatiotemporal radiation biomedicine

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The innovating advent of powerful TW laser sources (~10E19 W cm-2) and laser plasma interactions providing ultra-short relativistic particle beams (electron, proton) in the MeV domain open exciting opportunities for the simultaneous development of high energy radiation femtochemistry (HERF) and ultrafast radiation biomedicine.

Femtolysis experiments (Femtosecond radiolysis) of aqueous targets performed with relativistic electron bunches of 2.5-15 MeV give new insights on transient physicochemical events that take place in the prethermal regime of confined ionization tracks. Femtolysis studies emphasize the pre-eminence of ultra-fast quantum effects in the temporal range 10E-14 - 10E-11 s. The most promising advances of HERF concern the quantification of ultrafast sub-nanometric biomolecular damages (bond weakening and bond breaking) in the radial direction of a relativistic particle beam. Combining ultra-short relativistic particle beams and near-infrared spectroscopic configurations, the real-time interaction cross section between very-short lived quantum probe and biomolecules can be investigated in the temporal window 50 - 3000 fs. The eigenstates of transient p-like excited prehydrated electrons are used as ultrashort quantum probe for which the gyration radius is about 6 angströms. Laser-plasma accelerators based high energy radiation femtochemistry would foreshadow the development of real-time radiation chemistry in the prethermal regime of nascent ionisation clusters.

These advances would be very useful for future developments in biochemically relevant environments (DNA, proteins) and more complex biological systems such as living cells. The first investigation of a single-shot irradiation performed at high energy level (90 MeV) and very high dose rate, typically 10E13 Gy s-1, demonstrates that a measurable assessment of immediate and reversible DNA damage can be explored in nucleus. This breakthrough would permit the innovative concept of bionanodosimetry developed on the time scale of molecular motions, i.e. angstrom or sub-angstrom displacements and open new perspectives in the emerging domain of ultrafast radiation biomedicine such as pulsed radiotherapy.

8433-41, Session 9

Power balance on the SG-III prototype facility

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1. Introduction

High-performance, laser-driven inertial confinement implosions require that the time-averaged radiation asymmetry must be kept to a minimum to achieve high-yield implosions . The random radiation asymmetry mainly arises from power imbalance of beams. Two types of variations in laser performance lead to power imbalance: random variations and systematic (repeatable) variations. This article describes the efforts to improve the power balance of SG-III prototype facility. Time-division multiplexing (TDS) in frontend and angle detuning in final optics assembly (FOA) are applied in the facility, and then the power imbalance of systematic variations can be eliminated entirely.

This article is structured as follows: In section 2 we will describe the power balance characters of SG-III prototype facility; some new methods will be introduced to improve power balance. Section 3 summarizes the experiments; the compared results with new methods will be analyzed. Section 4 is the conclusion.

2. Power balance and the improvements on the SG-III prototype facility

The pulse sources are only one optical pulse generation (OPG) subsystem on SG-III prototype facility. Systematic differences are caused by differences in gain, transmission, beam area, and frequency conversion for the individual differences. The way to compensate for systematic differences of NIF is to increase the injected energy to consistently low beams and decrease injected energy to consistently high beams to minimize the systematic power imbalance. However, with energy adjusted to meet energy balance, the power controlling level is limited.

To improve systematic differences, each beam pulse being controlled independently is necessary. We applied two methods to realize the function. One is TDS in Frontend; it uses arbitrary waveform generation (AWG) to generate a long pulse containing a series of optical pulses, after splitter, the acousto-optical modulation is used to fetch the optical shapes to preamplifier subsystem. The other is angle detuning in FOA; the same preamplifier pulse being injected to two main amplifiers may introduce different variations, the detuning angle is controlled to compensate the differences.

3. Experiments

To validate the effectivity of the applied methods, the iteration procedure to adjust the optical shape in frontend to meet power balance was built on the SG-III prototype facility. 3 steps shape was selected as pulse shape. It was found that with 2-3 shots the uniform shapes can be obtained. It concluded that with the TDS method the uniformity of pulses can be improved effectively, the residual variations were only random variations.

4. Conclusion

To improve power balance on the SG-III prototype facility, some way of beam pulse being independently controlled was studied. TDS in Frontend and angle detuning in FOA was proposed. With the two methods applied in the facility, the iteration procedure was built. The effectivity was proved by 3 steps pulses with the experiments, and it shows that the systematic variations of power imbalance can be eliminated entirely.

8433-42, Session 9

Tapered fiber phase conjugation for high-power all-solid-state laser with high repetition rates

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A high power multi-pass diode-pumped solid-state MOPA system with large core diameter tapered quartz fiber as phase conjugator was developed. Over 69% SBS reflectivity and 101 mJ double-pass output energy were obtained with 1000 Hz repetition rate when incident energy was 38 mJ with 24 ns pulse width. The beam quality (M2) was better than 2. The phase conjugator was fabricated by a taper shaped fiber with 1mm diameter at the incident end and 0.4mm diameter at the output end. The pulse width was compressed to 6 ns from 24ns.

8433-43, Session 9

Development of 500mm array-lens beam sampler

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During the field of the space optics and the research on the military affairs, large aperture optics components have been the important parts of them. In advanced optical manufacturing technologies, the large astronomical telescopes and the large mirrors are being developed in many countries. And for testing the parameters of the aperture optics components, the large aperture beam should been transformed to the slender beam so that the photoelectricity detector can survey it. To achieve the process it needs the optics dwindle lens or the focus lens. As the aperture of the mirror increases, the price of the measure system and the difficulty of the technique increase non-linear.

Wavefront sampling is important for beam parameters measurement. A new method to perform the large aperture beam sampling with array-lens was put forward. This paper combines the large aperture emission optics system and wavefront measuring, adopts the array-lens to implement sampling the large aperture wavefront. Basing on the practicality testing work and the research demanding, the array-lens of 500mm with 25×25 sub apertures formed the rotundity aperture(33 lenses are canceled each corner and 9 lenses are canceled in the center.) are designed. A 25×25 array-lens of wavefront distortion measurement was designed, and an experimental system was settled up.

The beam sampler measures the wavefront aberration that contains two parts of the large aperture beam, which are the aberration of the system oneself and the aberration of the pending beam

$W=W_s+W_b$ (1)

To demarcate the beam sampler to get the aberration of the system oneself, so the aberration of the pending beam is

$W_b=W-W_s$ (2)

The perfect parallel beam is used to demarcate the large aperture array-lens beam Sampler. And a large aperture wavefront of distortion was measured by the set. It shows the experiment result that is accordance to the theory account. So the large aperture beam Sampler for demarcating oneself aberration can be used to measure the aberration of the large aperture wavefront.

8433-44, Session 10

Grating waveguide structures for intracavity generation of beams with azimuthal polarization in an Yb:YAG thin-disk laser

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We report on the design, fabrication, and spectroscopic characterization as well as on intra-cavity employment of grating waveguide structures (GWS) for the generation of beams with azimuthal polarization in an Yb:YAG thin-disk laser. Two different GWS concepts are used for the polarization shaping: the first is based on a resonant reflection behavior whereas the second uses the coupling mechanism to a leaky-mode. In both cases the structure combines a multilayer coating and a sub-wavelength grating.

The resonant reflection structure comprises a partial reflector (R~88%) and a wave guiding layer. The parameters of the grating (which is integrated into all layers) are designed in order exploit the abnormal reflection caused by constructive interference and was designed with a nominal peak reflectivity higher than 99.9% at the laser wavelength i.e. 1030 nm and within a narrow spectral bandwidth (2-3 nm FWHM).

The leaky mode structure is composed of a standard HR mirror and a grating which was designed to excite a leaky mode of the structure. This leads to a reduction of the reflectivity for one polarization at 1030 nm whereas the orthogonal polarization is not affected and experiences a high reflectivity.

By fabricating these elements with circular grating geometries one can generate beams with either radial or azimuthal polarization. Here we discuss the latter case where azimuthally polarized beams with a power of up to 100 W, an optical efficiency of 40.1%, and high polarization purity were generated. The beam quality factor M^2 of the emitted beams was measured to be approximately 2.2 which is close to the theoretical optimum. Moreover, the effect of temperature load in the GWS on the performance of the device will be discussed in details.

8433-45, Session 10

Spectroscopic properties of newly flux grown RE2O3:Yb3+ (RE=Y,Gd,Lu) laser crystals for high-power diode-pumped systems

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Developing large laser grade cubic rare-earth sesquioxides (RE_2O_3, RE=Y, Gd, Lu) single crystals doped with Yb^{3+} ions stands as one of the most challenging endeavours of today's crystal growth [1,2]. Recent studies on cubic RE_2O_3 single crystals have demonstrated the laser potential of these materials and highlighted the extreme thermodynamic conditions in which their growth takes place [1-3]. In particular, the laser performances of $Lu_2O_3:Yb^{3+}$ crystals make it likely to outperform better-known rivals such as $YAG:Yb^{3+}$ or $KY(WO_4)_2:Yb^{3+}$ for 976 nm diode-pumped systems [4]. After having briefly presented several mm^3-sized Yb^{3+}-doped Y_2O_3, Gd_2O_3 and Lu_2O_3 single crystals which were recently grown by a newly designed high-temperature solution growth method [5], and characterized by means of X-ray diffraction, Fourier transformed infrared (FTIR) spectroscopy and electron probe microanalysis (EPMA), we will present the spectroscopic characterizations (absorption and emission cross sections, visible anti-Stokes emission, fluorescence decays) of these new cubic $RE_2O_3:Yb^{3+}$ (RE=Y,Gd,Lu) single crystals. We shall emphasize that this flux growth process allows for achieving optimal doping for high-power laser applications, impedes the dissolution of OH^- groups in the crystals and hinders the formation kinetics of Yb^{3+} pairs that would lead to detrimental cooperative emission around 500 nm. The optimal ms-long experimental lifetime and the large energy storage parameter make these new crystals a priori competitive for high average or peak output powers delivery under diode pumped quasi-four level operation. The first laser tests carried out on these crystals under diode pumping at 976 nm will be presented.

1. A. Yoshikawa and V. Chani, MRS Bulletin, 2009, 34, 266-270.

2. Akihiro Fukabori, Valery Chani, Kei Kamada, Federico Moretti and Akira Yoshikawa, Cryst. Growth & Des., 2011, 11, 2404-2411.

3. R. Peters, C. Kränkel, K. Petermann and G. Huber, J. Cryst. Growth, 2008, 310, 1934-1938.

4. C. R. E. Baer, C. Kränkel, C. J. Saraceno, O. H. Heckl, M. Golling, R. Peters, K. Petermann, T. Südmeyer, G. Huber and U. Keller, Optics Letters, 2010, 35 (13), 2302-2304.

5. P. Veber, M. Velázquez, V. Jubera, S. Pechev and O. Viraphong, CrystEngComm, 2011, 13 (16), 5220-5225.

8433-46, Session 10

Ytterbium doped Sc2SiO5 in thin-disk laser configuration

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We present first investigations of $Yb:Sc_2SiO_5$ (Yb:SSO) in thin-disk laser configuration. First results regarding the characterization of the crystal and its laser operation will be discussed.

Yb:YAG is up to date the best developed and most used thin-disk laser material. The initial choice of this material was however not motivated by its suitability for the generation of femtosecond pulses since its limited spectral gain bandwidth does not support pulse durations shorter than approximately 700 fs in efficient high-power thin-disk laser operation. As there is a tremendous progress in research and development of ultrafast laser systems for many new applications in fields like medicine and material processing, the investigation and further improvements of laser active gain materials suitable for high power cw- and mode-locked operation have attracted a great attention.

Among other laser active materials, Ytterbium doped scandium silicon oxide (Sc_2SiO_5) is an interesting candidate for the above mentioned laser operations. Experimental results with Yb:SSO as bulk laser active material have already shown the potential of this crystal. The material $Yb:Sc_2SiO_5$ provides good thermo-mechanical properties such as a high thermal conductivity (7.5 W/(Km) and a negative thermal coefficient dn/dT (-6.3 10^{-6} 1/K) which is favorable to keep the thermally induced optical distortion small for efficient high-power-fundamental-mode operation. The broad emission bandwidth $\Delta\lambda_{em}$ as well as the large absorption cross-section abs,pump makes the material promising for the development of highly efficient passively mode-locked systems with pulse durations in the fs-range.

Demonstration of 10 W of CW-output power with an optical efficiency of 25.4 % in fundamental-mode operation is shown. The output power can further be scaled by increasing up the pump spot diameter and by optimizing the laser resonator configuration. Further experiments on power scaling as well as on passively mode-locked operation are under progress and will be presented during the talk.

8433-47, Session 10

High-efficiency wavelength and polarization selective grating-waveguide structures for Yb:YAG thin-disk lasers

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We report on a grating-waveguide structure with a high diffraction efficiency used in Littrow configuration to select (and tune) the wavelength of an Yb:YAG thin-disk laser. The structure is composed of a multilayer HR coating, on which a low index layer was deposited. A grating with a period of 560 nm and a groove depth of about 70 nm was integrated into the topmost high-index (Ta_2O_5) layer of the structure.

The simulation results show that the diffraction efficiency in the -1st

order can reach a value of 99.9% for TE polarization whereas it is only about 10% for TM polarization. The grating was fabricated by standard interference lithography followed by reactive ion beam etching down to the desired grove depth. However, the spectroscopic measurement exhibited a diffraction efficiency of only 99%. This is due to the discrepancies between the design parameters of the grating and the realized structure - mainly the differences in groove depth and duty-cycle. Although the efficiency is lower than desired, the device was placed as end mirror into the resonator of a fundamental-mode (M^2~1.1) Yb:YAG thin-disk laser. An output power of up to 69.3 W could be obtained from the laser, corresponding to an optical efficiency of 27.5%. The spectral bandwidth of the emitted beam was measured using an Optical Spectrum Analyzer to be less than 20 pm. We also showed a tuning range of about 26 nm (1022-1048 nm). With a commercially available Stokes polarimeter, the degree of linear polarization was measured to be higher than 99% over the whole power and wavelength tuning range. Further improvements of the structures (higher efficiencies) as well as the latest laser results will be discussed in detail during the presentation.

8434-01, Session 1

Graphene for photonics applications

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

No abstract available

8434-02, Session 1

Soliton pattern formations in figure-of-eight laser

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Passively mode-locked fiber lasers have demonstrated their ability to generate several types of soliton complexes, especially in the anomalous dispersion regime where the soliton energy quantization favours multiple pulsing. In particular, bound states of few pulses have been observed independently of both the dispersion regime and the exact physical mechanism of mode-locking. The scaling up of the output power of fiber lasers in recent years has allowed to considerably increase the number of coexisting solitons in passively mode-locked fiber lasers. Thus the number of interacting pulses has undergone a big step from a few tens to several hundreds, resulting in new and complex pattern formation dynamics. Concerning such large numbers of self-organized dissipative solitons, all the recent results have been obtained using the nonlinear polarization rotation (NLPR) technique to passively mode lock the fiber laser. A bound state containing several hundreds of pulses was first reported in [1] (soliton crystal). A "rain of solitons" dynamics has also been reported in a similar laser configuration [2]. Several ordered and disordered patterns presenting analogy with the states of matter were observed in the erbium-doped double-clad fiber lasers [3]. A reconstruction has been performed for a soliton gas, a soliton liquid, a soliton polycrystal and a soliton crystal. We have realized a figure-of-eight (F8L) erbium-doped double-clad fiber laser in which the mode-locking is realized with a nonlinear amplifying loop mirror. Experimental results demonstrate that this configuration can generate a large variety of soliton complexes: soliton crystal, soliton gas, soliton liquid and a polycrystal state. These results suggest that such soliton states are an intrinsic feature of dissipative solitons in a fiber laser independently of the exact mode-locking mechanism. In addition, the F8L has revealed a diphasic mixture in which there is coexistence of soliton crystal and liquid.

[1] A. Haboucha et al., Phys. Rev. A 78, 043806 (2008).

[2] S. Chouli et al., Phys. Rev. A 81, 063829 (2010).

[3] F. Amrani et al., Appl. Phys. B. 99, 107 (2010).

8434-03, Session 1

Dynamic multimode analysis (DMA) of passively Q-switched intracavity frequency-doubling solid state laser

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We derive a new model to simulate passively Q-switched intracavity frequency-doubling solid-state laser. By introducing a nonlinear loss term caused by frequency-doubling crystal into the rate equations ,we can express the effect of second-harmonic generation (SHG). To the best of our knowledge, the equation describing photon number at double-frequency is introduced for the first time. We apply a finite volume discretization on gain medium, saturable absorber and frequency-doubling crystal. ``Dynamic Multimode Analysis (DMA)" and several Gaussian modes are utilized. At the end, numerical results of passively Q-switched intracavity frequency-doubling solid-state laser are presented. The simulation results show a chaotic behavior of laser.

In order to realize the 3D simulation, we mainly use two technics: One is that common rate equations are extended to a set of 3D multimode rate equations,which calculate photon number for different modes separately. The other is to take into account a finite volume discretization.

8434-04, Session 1

High-beam-quality narrow-linewidth 13-W continuous-wave fiber-based source at 970 nm

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High-power, continuous-wave (cw) sources at 970 nm are of considerable interest for a variety of applications including biological sensing [1]. For many such applications, good spatial beam quality in addition to high output power is imperative. Although there are different possible sources at 970 nm, such as diode lasers, Ti:sapphire lasers, and cw ytterbium-doped photonic crystal fiber lasers, attainment of good beam quality (M2 factor) together with high output power and narrow linewidth still remains a challenge. Fiber-laser-based single-pass second-harmonic-generation (SP-SHG) at 970 nm offers an attractive alternative to accomplish all the above requirements in a compact, robust and cost-effective design.

Here, we report a fiber-laser-based cw source at 970 nm generating stable, high-power, narrow-linewidth radiation in good beam quality [2]. Using direct SP-SHG of a cw thulium fiber laser at 1940 nm in a 40-mm-long periodically-poled LiNbO3 crystal, we have generated 13.1 W of output power at 970 nm for a fundamental power of 40 W. For the attainment of the highest efficiency, we studied different spatial mode-matching conditions and achieved a SP-SHG conversion efficiency as high as 32.7% for confocal focusing parameter of ~2.86, which is almost equal to theoretical optimum focusing parameter of ~2.84, in the cw limit [3]. We found that the phase-matching temperature (TQPM) is decreased, while the temperature acceptance bandwidth is increased with tighter focusing. These observations have been theoretically verified by calculating the propagation length of divergent beam components for different fundamental beam waists. We also theoretically verified the increase in experimental TQPM with the increase in fundamental power. The generated second-harmonic output exhibits a passive power stability better than 1.4% (1σ-value) over 1 hour and has an FWHM linewidth of 0.3 nm in TEM00 spatial beam profile with M2<1.6. Relevant theoretical calculations for the characterization of SP-SHG in the crystal and elaborate discussion on experimental results will be presented.

References

1. I. Goykhman, B. Desiatov and U. Levy, "Ultrathin silicon nitride microring resonator for biophotonic application at 970 nm wavelength," Appl. Phys. Lett. 97, 081108-1-3 (2010).

2. K. Devi, S. Chaitanya Kumar and M. Ebrahim-Zadeh, "13.1 W, high-beam-quality, narrow-linewidth continuous-wave fiber-based source at 970 nm," Opt. Express 19, 11631-11637 (2011).

3. G. D. Boyd and D. A. Kleinman, "Parametric interaction of focused Gaussian light beams," J. Appl. Phys. 39, 3597-3639 (1968).

8434-66, Session 1

Generation of picoseconds pulses around 6.45 µm by synchronously pumped OPO using AgGaS2 and CdSiP2

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In this work, we describe the performance of a synchronously pumped optical parametric oscillator (OPO) using type I and type II phase matching in a silver thiogallate(AgGaS2 or AGS) and non critical phase matching cadimium silicon phosphade (CdSiP2 or CSP) crystals quasi-collinearly pumped at 1064nm by a 25Hz picosecond passive and active mode-locked Nd:YAG laser. The largest tuning range is achieved with AGS crystals. Indeed, tuning from 2,9 to 7,8µm and 4,4 to 8,6µm is obtained for type I and type II AGS, respectively. The angular and temperature tuning curve of CSP is limited to 6,45 - 7 µm. Theses experimental tuning curves are compared to calculated tuning range. However, CSP enables to achieve higher conversion efficiency at 6.45µm. Indeed, replacing AGS by CSP in the OPO enables to decrease the pump power at oscillation threshold by more than one order. This, combined with an higher damage threshold enables to operate the OPO about 20 times above oscillation threshold while the fragility of AGS crystal limits the operation of the same OPO at only about 2 times above oscillation threshold. Pump transmission and depletion figures for crystals complete our study. Our results demonstrate the suitability of a CSP-based OPO for generating high-power 6.45µm picosecond beam, and possible surgical applications.

8434-06, Session 2

Nonlinear optics in tapered silicon fibers

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Tapered bres provide a unique means to manipulate pulse propagation for use in all-optical signal processing applications. Recently, we have demonstrated a new class of taper that is fabricated from our silicon core optical bre platform. Owing to the high core-cladding index contrast, these silicon tapered bres can accommodate large taper ratios over short millimetre lengths without introducing any appreciable loss. Such strong tapers allow for unprecedented control over the dispersion and nonlinearity parameters for the tailoring of femtosecond pulse propagation. Using numerical simulations based on realistic tapered bres with micro to nanoscale core dimensions, we have shown that it is possible to exploit the longitudinally varying waveguide parameters for nonlinear pulse shaping in both the normal and anomalous dispersion regimes. In the normal dispersion regime, we have made use of a decreasing dispersion prole to generate linearly chirped parabolic pulses which allow for high power distortion-free propagation. Similarly, in the anomalous regime a decreasing dispersion prole can be used to compensate for the material losses to allow for soliton propagation, and even soliton compression to generate ultrashort pulses. Due to the broad optical transmission window of silicon, we anticipate that nonlinear pulse shaping in tapered silicon bres and waveguides will nd use not only in the telecoms band, but also extending into the mid-infrared for applications in the life sciences.

8434-07, Session 2

Optimized wavelength conversion in silicon waveguides based on off-Raman-resonance operation

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Over the past decade there has been growing interest in using the nonlinear optical effects in silicon for wavelength conversion in the near-infrared telecommunication domain. Both the third-order Raman and the third-order Kerr susceptibilities of silicon can be exploited for this purpose as both allow establishing four-wave-mixing. Since the Raman- and Kerr-based four-wave-mixing interactions occur between coherent waves at three different frequencies, the phase mismatch, i.e. the relative change along the waveguide of the phase difference between the waves, plays an essential role for the wavelength conversion efficiency.

Starting from the propagation equations for the involved pump, Stokes and anti-Stokes waves and from an extended formalism for the phase mismatch between these waves, we investigate how the four-wave-mixing efficiency in silicon waveguides is influenced by the frequency difference between the pump and Stokes input waves. By means of numerical simulations we show that, by detuning this frequency difference slightly away from Raman resonance, the conversion efficiency does not necessarily decrease, but can even be more than doubled as compared to Raman-resonant operation. At the same time, other values of the frequency detuning that still remain well within the Raman line width can lead to a more than 10 dB decrease in efficiency. As such, we show that a high-resolution tuning of the frequency difference is not only necessary to obtain an optimal conversion efficiency, but also to avoid the detrimental efficiency decrease to which an inadequate detuning value can lead. Finally, we discuss how the pump-Stokes frequency difference that is optimal for wavelength conversion varies with the length of the waveguide and with its dispersion characteristics. The presented results offer new insights in the operation of silicon-based wavelength converters and as such are of importance both for the design of these components and for the implementation of wavelength conversion experiments.

8434-08, Session 2

Nonreciprocal lasing and polarization selectivity in silicon ring Raman lasers based on micro- and nano-scale waveguides

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Shortly after the first demonstration of stimulated Raman scattering in silicon almost a decade ago, researchers started developing silicon-based Raman lasers with all kinds of cavity designs. Nowadays one mostly uses monolithic integrated ring resonators for this category of light sources. Nevertheless, important aspects of silicon ring Raman lasers, such as the directionality and the polarization behavior of the lasing radiation, have not yet been investigated in detail. A thorough understand of these aspects is, however, of key importance to fully exploit the application potentialities of these laser sources.

In this paper, I present a generic model that describes the lasing characteristics of continuous-wave circular and racetrack-shaped ring Raman lasers based on micro- and nano-scale silicon waveguides, including their lasing directionality and polarization behavior. This model explicitly takes into account the effective Raman gain values for forward and backward lasing, the Raman amplification in the bus waveguide, and the spatial gain variations for different polarization states in the ring structure. I show numerically that ring lasers based on micro-scale waveguides generate unidirectional lasing in either the forward or backward direction because of an asymmetry in nonlinear losses at near-infrared telecommunication wavelengths, whereas those based on nanowires yield only backward lasing due to a non-reciprocity in effective gain. Furthermore, the model indicates that backward lasing can yield a

significantly higher lasing output at the bus waveguide facets than lasing in the forward direction. Finally, considering a TE-polarized pump input for a (100) grown silicon ring Raman laser, I demonstrate numerically that the polarization state of the lasing radiation strongly depends on whether micro-scale or nano-scale waveguides are used. With these new insights it becomes possible to exploit silicon ring Raman lasers in a range of new applications where nonreciprocal behavior or polarization selectivity are of crucial importance.

8434-09, Session 2

Extending the phase mismatch formalism for silicon-based wavelength converters

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For several years now, the strong third-order nonlinear optical effects displayed by silicon waveguides have been extensively investigated for, amongst others, wavelength conversion at near-infrared telecommunication wavelengths. This functionality can be accomplished by means of Raman- and Kerr-based four-wave-mixing. Since these processes involve nonlinear interactions between coherent waves at three different frequencies, the phase mismatch, i.e. the relative change along the waveguide of the phase difference between the waves, plays an essential role for the efficiency of the wavelength conversion.

We present a generic approach to determine the phase mismatch for any optical nonlinear process. When applying this approach, which is based on the evaluation of local phase changes, to Raman- and Kerr-based four-wave-mixing in silicon waveguides, we obtain a novel expression for the phase mismatch which is more accurate as compared to the conventional definition; and which contains additional contributions due to the dispersion of the four-wave-mixing processes, the so-called “four-wave-mixing dispersion”. By means of numerical simulations, we show that this additional dispersion has a significant impact on the evolution of the phase mismatch along the waveguide, and thus on the conversion efficiency. As such, our extended phase mismatch formalism provides additional insights regarding the nonlinear four-wave-mixing interactions in silicon waveguides and allows to improve the operational characteristics of a variety of silicon-based nonlinear optical devices.

8434-10, Session 2

Sub-two-cycle soliton self-compression in a tapered tellurite photonic crystal fiber

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Tellurite and chalcogenide glasses have been the subject of intense investigations for nonlinear mid-IR applications due to their nonlinear indices higher than that of silica glass by more than one to three orders of magnitude, respectively. Investigating the nonlinear propagation, with low input pulse energies, in tellurite fibers has been shown to be more advantageous than that in highly chalcogenide glasses avoiding the limitation of the two photon absorption; one of the major material property of chalcogenide glasses. Until recent years, with the remarkable interest in sub-wavelength waveguides, the introduction of highly nonlinear photonic nanowires with anomalous group velocity dispersion (GVD) has enormously contributed in the study of soliton self-compression and the generation of few to single-optical- cycles. Tapering photonic crystal fibers has shown that the overall-GVD can be highly engineered and shifted to the mid-IR wavelengths region [1].

In this paper, we numerically report on the generation of sub-two-cycle mid-IR pulses in a highly nonlinear tellurite tapered photonic crystal fiber (TPCF). The composition of the tellurite TPCF is 76.5TeO2-6Bi2O3-11.5Li2O-6ZnO (mol%). We demonstrate maximum soliton self-compression of a pre-chirped hyperbolic-secant 200 fs pulse down to 19.1 fs by pumping an 8mm-long tellurite TPCF at 2.9 µm with an input energy of 1 nJ. The tellurite nanowire has a waist diameter of 1.3 µm, hole diameter d= 0.3 µm and pitch =0.8 µm. The study is based on the optimization of initial chirp in order to generate efficient broadband soliton self-compression with the lowest input pulse energy. More than two octave spanning coherent single mode supercontinuum extending from 1675 nm to 3950 nm is generated. Tellurite tapered photonic crystal fibers present suitable waveguides and very promising for mid-IR low-power devices and applications.

[1] A. Ben Salem, R. Cherif, M. Zghal, “Tapered As2S3 chalcogenide photonic crystal fiber for broadband mid-infrared supercontinuum generation,” FIO 2011, San Jose, California, USA.

8434-05, Poster Session

Phase matching in defected core tellurite/ phospate composite nonlinear optical fiber

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The low loss and micro-structured chalcogenide optical fiber have been considered in this paper due to their unique nonlinear properties. These optical fibers have enormous potential and they are also unrestraint to tailor the design for obtaining promising dispersion properties. Furthermore, the analysis shows that third harmonic generation process has significant impact on the quasi phase matching in micro-structured fiber. It has been observed that conversion efficiency significantly increases when nonlinear contribution to propagation constant is considered for phase matching. The dispersion have been deduced for various core diameter to realize the dispersion compensation fiber (DCF). For this DCF the phase matching have been obtained for even and higher order dispersion with the optical pump pulse conditions. The coupled mode theory along with nonlinear Schrödinger equation has been used to reveal the optical properties of telluride optical fiber. The paper has been focused to investigate the effective index, pulse evolution, phase change, quasi phase matching and prediction of the super continuum bandwidth. For this the energy transfer to dispersive waves are explored. The study have been extended to realize the optical Kerr effect and Raman scattering influence over the optical intensity in the optical fiber.

8434-41, Poster Session

Cascaded sum and difference frequency generation (cSFG/DFG)-based wavelength conversion of short optical pulses

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Using ring type diversity scheme, a tuneable polarization insensitive cascaded sum and difference frequency generation (cSFG/DFG)-based wavelength conversion in a periodically poled LiNbO3 (PPLN) channel guide is investigated. This approach results in a tuneable output wavelength of the idler whereas the input signal wavelength can be kept fixed. In continuous wave (cw) regime, a conversion efficiency of ~ -7.5 dB has been achieved in a 70 mm long Ti:PPLN channel guide by 80 mW (20 mW) of coupled cw pump (control) power level with less than ± 0.5 dB of residual polarization dependence. The tuning range of the idler covers the whole C-band. In addition, calculated evolution of picosecond signal pulses during cSHG/DFG-based wavelength conversion is presented.

Four different input signal pulse widths of 1.4 ps, 3 ps, 5 ps and 9 ps with the peak powers of 100 mW were interacted with the 50 mW cw pump and control waves in a 70 mm long Ti:PPLN waveguide.

Generated SF pulses in the 0.775 µm experience the broadening and distortion of its shape due to a walk-off (~ 3.2 ps/cm) with the signal pulse in the 1.5 µm band caused by the group velocity dispersion (GVD). Simultaneously the SF pulses have again a walk-off (~ 3.2 ps/cm) with generated idler pulse via DFG. Thus, GVD lead to a broadening of the converted signal (idler) pulse. as compared with the input signal pulses.

If this broadening does not result in loss of information (caused by any overlapping of a pulse with the neighboring pulses), tuneable cSFG/DFG-based wavelength conversion from signal wavelength to idler wavelength can be successfully realized for system applications. Simulated results shows that if the input signal pulse is assumed to be 1.4 ps, then even tuneable conversion of 160 Gb/s signal is possible.

The investigated scheme, with its performance to convert short optical pulses, exhibit a high flexibility for wavelength conversion, which can be potentially exploited in practical optical communication systems.

8434-42, Poster Session

Design of ultra-compact low-power all-optical modulator by means of dispersion engineered slow light regime in photonic crystal Mach-Zhender

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We present a new design for an ultra-compact low power all-optical modulator based on dispersion engineered slow-light regime in photonic crystal Mach-Zehnder modulator(PhC-MZM), selectively infiltrated by nonlinear optical fluids.

In procedure of designing such a device we apply dispersion engineered waveguides in MZM structure to increase nonlinear effect which brings us low power operation and small size modulator . Besides, Utilizing dispersion engineered waveguides in short arms enhances the output power by decreasing loss through the waveguides. Moreover, compact all-optical devices can operate faster in comparison with the conventional ones. Hence the greater the refractive index changes by nonlinear effect will result the smaller the MZM. In this paper we apply the slow light regime waveguides which is achieved by optofluidic infiltration. Taking advantages of high nonlinear effects of optofluidics enable us to design an ultra compact modulator which can be easily modified and tuned by changing the refractive indices of optical fluids.

The dispersion-less slow-light regime enhancing the nonlinearities enabled a 22-µm long PhC-MZM to operate as a modulator with an input power as low as 3mW/µm. Simulations reveal that the switching threshold can be controlled by varying the optofluidic infiltration. As a matter of fact by an input power of 11mW/ µm one can achieve a switching window of 40 Ps.

8434-43, Poster Session

All-fiber broadband supercontinuum generation in a single-mode high-nonlinear silica fiber

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The high nonlinear fibers (HNLFs) based on germanium- and fluorine-doped silica fiber has a low dispersion slope and a small effective area. Because of the small effective area, the effective nonlinear parameters of the silica HNLFs are several times higher than that of standard singl-mode fiber (SSMF). Although the nonlinear parameters of silica HNLFs are still significantly smaller than those of the photonics crystal fibers (PCFs), the most important advantage of silica HNLFs is that they can be fusion spliced to the pump fiber lasers directly with very low loss and can use the pump energy with the highest efficiency. This makes silica HNLFs be the practical candidate for all-fiber SC source. In this work, we demonstrate an all-fiber broadband supercontinuum (SC) source with high efficiency in a single-mode high nonlinear silica fiber. The SC is pumped by the 1557 nm sub-picosecond pulse, which is generated by a homemade passively mode-locked fiber laser with a saturable absorber incorporating nanotubes (SAINT) in a ring cavity, amplified by an EDFA and compressed to 600 fs. The HNLF used in experiment has the zero-dispersion wavelength of 1584 nm with low dispersion slope. The pump pulse is in the normal dispersion region and the SC generation is initiated by the SPM effect. When the long-wave band of the spectrum is extended to the anomalous dispersion region, the soliton self-frequency shift and intra-pulse Raman effects extend the spectrum further. Meanwhile, the dispersive waves shorter than 1100 nm begin to emerge because the phase matching condition can be satisfied easily in this fiber and the intensity increases with the addition of pump intensity. The broad SC spectrum with the spectral range from 840 to 2390 nm is obtained at the pump peak power of 46.71 kW, and the 10 dB bandwidth from 1120 nm to 2245 nm of the SC covers one octave assuming the peaks near 1550 nm were filtered. The SC has the repetition rate of 16.7 MHz, and some satellite pulses are generated during the nonlinear process. The SC source system is constructed by all-fiber components, which can be fusion spliced together directly with low loss less than 0.1 dB and improves the energy transfer efficiency from the pump source to the SC greatly. The maximum SC average power of 332 mW is obtained for the total spectral range, and the slop efficiency to the pump source is about 70.3%, which will be lower when the peaks near 1550 nm are filtered, but is higher than those in PCFs. The spectral density for the 10 dB bandwidth is in the range from -17.3 to -7.3 dBm/nm. This SC source will have great applications in optical communications, optical coherence tomography, frequency metrology and spectroscopy due to its all-fiber structure, broad bandwidth, high spectral density and high efficiency.

8434-44, Poster Session

Surface wave modulation instability in sbn-61

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Surface wave (SW) modulation instability (MI) in niobate - barium strontium (SBN-61) at light wavelength of 0.53 mcm is investigated experimentally. We consider SW MI occurrence and development due to “drift” photorefraction (i.e. in presence of biased dc electric field). Influence of CW back side illumination on SW MI put in force with similar CW laser of same wavelength.

It is found that SW MI in SBN-61 due to “drift” photorefractivity occurs when biased electric field excess threshold value and is manifested as pattern of filaments. Its structure depends on electric field value and polarity. SW MI develops in three stages: at first stage biased electric field less than 500V/sm. At this stage SW transverse intensity distribution, which has form of regular bright strips, is “deformed”. Nevertheless, SW structure remains unchanged. Value of biased electric field at second stage of SW MI in the range between 500V/sm and 1000 V/sm. Transverse distribution of SW intensity at this stage is changed abruptly, and looks like as chaotic pattern of bright spots, not being in accordance with SW intensity distribution. Increasing of biased electric field leads to irregular oscillations of bright spots pattern with increasing amplitude. Thus, structure of SW transverse intensity distribution is loose at the second stage. At third stage biased electric field exceeds 1000V/sm. In this case light vanishes from SBN-61 surface region.

SW induces photorefractive nonlinear waveguide and propagates in SBN-61 at the same time as its mode. “Drift” - type SW MI, arising when electrical field is applied in direction of SBN-61 optical axis, at first stage leads to photorefractive waveguide mode “deformation” and at third stage leads to its frequency “cutoff” change. Backside illumination has stabilizing effect on SW, hindering MI.

8434-45, Poster Session

Phthalocyanines, porphycenes, and corroles: nonlinear optical properties and ultrafast dynamics

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Phthalocyanines, Porphycenes, and Corroles are macromolecules with large number of delocalized pi electrons. The response of these electrons to the short laser pulses determines their applicability in various applications such as optical limiting, optical single processing etc. A meticulous understanding of their performance using different pulses and at diverse wavelengths is indispensable to extract their potential. Herein we try to compare and contrast the nonlinear optical performance of these molecules in the ns, ps, and fs time domains. The nonlinear optical coefficients and figure of merits were estimated from the Z-scan data using different pulses over a range of input wavelengths. Ultrafast excited state dynamics of these molecules were studied using the pump-probe and degenerate four wave mixing techniques. Results from these studies will be presented in detail.

References

1. S. Venugopal Rao et al. Chem. Phys. Lett. 514, 98-103, 2011.

2. S. Venugopal Rao et al. Mat. Sci. Appln. 2, 299-306, 2011.

3. S. Hamad et al. J. Porphy. Phth. In Press, 2011.

4. S. Venugopal Rao Proc. SPIE 7728, 77281N, 2010.

5. S. Venugopal Rao et al. Proc. SPIE, 7197, 719715, 2009.

6. T. Sarma et al. Org. Lett. 13(2), 188-191, 2011.

8434-46, Poster Session

Protein-based high-speed all-optical logic

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Photonics is considered to be a complementary of conventional electronics in future informational technologies. Having the theories well-developed for optical data processing, the basic problem is to find proper nonlinear optical (NLO) materials that are able to actively control optical circuits.

Suitable NLO materials with high stability and sensitivity are being intensively researched [1]. Besides organic and inorganic crystals, chromoprotein bacteriorhodopsin (bR) has generated the most interest [2, 3] for optoelectronic applications. bR, isolated from the outer cell membrane of the bacterium Halobacterium salinarum, is the simplest known ion pump, and one of the best-characterized membrane proteins. Upon illumination it transports protons across the membrane, meanwhile the molecule changes its optical absorption, refractive index and charge distribution. These properties can be used separately or simultaneously in opto-electronic devices [4-7]. The operation of bR-based ultra high-speed all-optical switching has been demonstrated [8], and is expected to bring about a breakthrough in all-optical information processing systems [9].

In the course of recent experiments we developed all-optical logic gates, based on our ultrafast integrated optical switching technique. With the help of photopolymerization, we developed miniature, single mode Mach-Zehnder structures. The principle of logical operations is based on a reversible change of the refractive index of the bacteriorhodopsin film over either or both arms of the interferometer.

[1] R.F. Service, Science 268, 1570 1995

[2] R.R. Birge, Sci. Am. 3, 66 1995

[3] N. Hampp, Chem. Rev. 100, 1755 2000

[4] P. Ormos et al., Appl.Phys. Lett. 80, 4060 2002

[5] J. Topolancik and F. Vollmer, Appl. Phys. Lett. 89, 184103 2006

[6] A. Dér et al., Photochem. Photobiol. 83, 393 2007

[7] L. Fábián et al., Appl. Phys. Lett. 97, 023305 2010

[8] L. Fábián et al., Opt. Exp. 19, 18861 2011

[9] E.K. Wolff and A. Dér, Nanotechnol. Percept. 6, 51 2010

8434-47, Poster Session

Ultrafast nonlinear optical studies of cyclo[4] naphthobipyrroles

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Expanded porphyrins belong to the class of porphyrinoids, where the macrocycle contains either more than four bridging carbon atoms, or more than four pyrrolic units, or a combination of both [1]. The significance of this class of compounds lies in their novel photophysical and nonlinear optical properties. Superior nonlinear optical coefficients are observed for aromatic expanded porphyrins with large number of -electrons owing to their unique structure [2]. In this regard, cyclo[8] pyrrole is unique, owing to its large planar 30-core macrocyclic ring in its diprotonated state. Here, all the eight pyrrole units are directly linked to each other through their α-positions [3]. Recently, we have synthesized, cyclo[4]naphthobipyrroles, a unique class of cyclo[8] pyrroles, where alternate pyrrole units are fused with naphthalene moieties. This adds more rigidity to the resultant cyclo[8]pyrrole along with extended conjugation [4]. Herein, we present some of our results from the picosecond nonlinear optical and pump-probe studies of these molecules. The nonlinear optical coefficients were extracted from the picosecond Z-scan measurements while the lifetimes of the excited states were recorded using picosecond degenerate pump-probe measurements at 800 nm. The values of two-photon cross-sections obtained for these molecules were in the range of 10^4 GM.

References

1. J. L.Sessler, A. Gebauer, S. J. Weghorn, The Porphyrin Handbook 2000, 2, 55-121.

2. H. Rath, J. Sankar, V. Prabhu Raja, T.K. Chandrashekar, A. Nag, and D. Goswami, “Core-Modified Expanded Porphyrins with Large Third-Order Nonlinear Optical Response,” J. Am. Chem. Soc., 2005, 127(33), 11608-11609.

3. D. Seidel, J. L. Sessler, V. Lynch, “Cyclo[8]pyrrole: A Simple-to-Make Expanded Porphyrin with No Meso Bridges” Angew. Chem. Int. Ed. 2002, 41, 1422-1425.

4. T. Sarma, P. K. Panda, “Cyclo[4]naphthobipyrroles: Naphthobipyrrole Derived Cyclo[8]pyrroles With Strong Near Infrared Absorptions” Chem. Eur J. 2011, accepted.

8434-48, Poster Session

Switching Faraday rotation on a molecular level

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In this work we present measurements of the switching of the Faraday effect in metal-organic compounds. Faraday rotation is the rotation of the plane of polarization of linearly polarized light under the influence of a magnetic field in the direction of propagation of the light. It is the magnetic equivalent of circular birefringence and is related to magnetic circular dichroism via the Kramers-Kronig transformation. The Faraday effect is used in optical isolators and magnetic sensors.

Faraday rotation and magnetic circular dichroism spectra have been calculated and measured for various nanoparticles, nanocomposites, magnetic fluids and metal-organic complexes. These measurements and calculations indicate that it is possible to change the magneto-optical response by changing the state of the molecule, such as a change in protonation or oxidation state. The molecular environment also influences the magneto-optical spectra of metal-organic complexes and organic molecules. Thus it is possible to change the Faraday rotation spectrum by modifying the molecular environment or the molecule itself. We have measured the reversible switching of the magneto-optical response by these principles. This easily induced reversible switching opens the possibility of new devices such as switchable optical isolators.

8434-49, Poster Session

Second-harmonic generation as characterization tool for Ge/passivation layer interfaces

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Because the germanium native oxide provides a bad quality interface, building metal oxide semiconductors (MOS) gate stacks on Ge requires passivation of the interface between the dielectric and the Ge channel. Different approaches to perform this passivation are available: depositing a silicon capping layer on top of the Ge channel, performing sulphur passivation, depositing high-k material (typically by means of Atomic Layer Deposition) directly on top of Ge, etc. The interface properties of these MOS stacks are important, because they determine the electrical properties of the whole structure. Dangling bonds induce extra energy levels within the band gap, which results in a loss of efficiency of turning a metal oxide semiconductor - field effect transistor on and off. Fixed charges at or near the interface enlarge the voltage needed for switching between on and off state as well. Also the smoothness of the interface plays an important role for other front-end-of-line processes. Hence, characterizing these interfaces is a key challenge in semiconductor fabrication. This can be achieved using Second Harmonic Generation (SHG) to probe the interface, because SHG is an inherent surface and interface sensitive technique. Also electrical differences can be probed by SHG. In this work, we present SHG as an excellent surface and interface characterization tool for semiconductors for passivated germanium samples. Different SHG responses are shown for germanium samples with a silicon capping layer, sulphur passivated Ge or high-k dielectric on top of Ge.

8434-50, Poster Session

Spectral measurements to probe the magneto-optical properties of commonly used organic dyes

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Faraday rotation is a magneto-optical effect whereby the plane of polarization of a linearly polarized light beam is rotated under influence of a longitudinal magnetic field. The extent to which materials show Faraday rotation can be characterized by the Verdet parameter expressed in degrees per Tesla per meter. In current applications based on Faraday rotation, such as Faraday isolators or magnetic field sensors, inorganic materials as e.g. yttrium iron garnets are used as rotating materials. Organic materials exhibiting high values of the Verdet parameter are very desirable due to among others facile processing, cost, abundant resources of starting materials available and applicability in new areas such as biomedical research. Pi-conjugated polymers as e.g. specifically designed polythiophenes and poly(arylene ethynylene) in certain conformations are among the few organic materials which have been shown to possess high values for the Verdet parameter. Using a purpose built optical setup, an investigation in the optical and magneto-optical properties of commonly used organic dyes in (bio-)chemical and (bio-) medical research was carried out. Using the gained knowledge, synthetic design paradigms for organic materials exhibiting high values of the Verdet parameter and applicable in a variety of scientific domains can be shaped up.

8434-51, Poster Session

Nonlinear characteristics of laser-induced incandescence of rough carbon surfaces

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It is well known that powerful laser pulse can heat light-absorbing microscoparticles suspended in various transparent matrices to a temperature up to 4000 Kelvin and as a result emission called laser-induced incandescence (LII) is observed. In this work we observe LII of light-absorbing carbon surfaces and investigate its properties.

A moderate-power Q-switched YAG-Nd^{3+} laser (wavelength 1064 nm, pulse duration 20 ns, power density $F=10$ MW cm^{-2}) was used for excitation of laser-induced incandescence of bulk carbon samples. The nanosecond laser pulse duration limits the depth of penetration of heat into the sample so the surface can be heated to a temperature of several thousands of Kelvin.

The average surface's temperature was estimated by approximating the experimental LII spectrum by Planck's function and by computer simulations of laser heating of a carbon surface. Thermal and optical properties of the surface material were taken into account when the simulation was implemented. It was assumed that the surface consists of cone-shaped hills. Both of the estimates of temperature are in agreement within the margins of ±100 K. For typical experimental conditions, the value of 2400 K was obtained.

According to computer simulations, local temperatures at a laser-heated rough carbon surface can differ significantly from the average temperature value: local temperature at the surface peaks can reach 3500 K while at the valleys it can be as low as 1000 K. It can be assumed that the LII properties depend on the characteristics of the heated surface and can be affected by the roughness of the investigated surface.

For LII signals integrated over the surface, I_{LII}, we also calculated the non-dimensional rate of the surface emission non-linearity, $\gamma = \Delta (\lg I_{LII}) / \Delta (\lg F)$. The obtained values of γ are within the margins of 7...10 that indicates significant non-linearity of LII. The experimental dependence of I_{LII} vs F confirmed the computed values of γ.

When a carbon surface is irradiated by a sequence of N laser pulses, an unusual dependence of I_{LII} vs N was discovered in the experiments. At the beginning the intensity of LII increases with N, but at a certain point I_{LII} begins to decrease. The analysis of theoretical dependence of I_{LII} on the height of the surface peaks showed that with height decreasing the intensity of LII increases to a certain point (when the height of the surface peaks is equal to 270 nm), after which the emission begins to fade. It gives the opportunity to suggest that such behavior of I_{LII} vs N can be explained by evaporation of surface material from the top overheated areas of the roughness peaks.

8434-52, Poster Session

Amplification of frequency-modulated similariton pulses in length-inhomogeneous active fibers

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Generation of stable self-similar frequency modulated optical pulses, referred to as similaritons, in an active (gain) medium with the normal group-velocity dispersion (GVD) opens up extensive advantages over the classical ways of optical pulse amplification. In the case of the optical pulse amplification in an anomalously dispersive medium, it is difficult to avoid various instabilities as well as Raman laser effect that could considerably distort the wave packet profile. However, in the normal GVD medium there also arise some definite problems. Some known methods

of the pulse amplification in homogeneous optical fibers are sensitive to the "unplanned" diameter variation of the mentioned fibers. Therefore, the use of "long" amplifiers (the length >100 m) with a low gain increment 0,1 m-1. In this case, the following parameters can be efficiently controlled over the optical fiber length (due to a relatively short amplifier length): the fiber core diameter, dispersion, and nonlinearity. The present work will analyses the dynamics of the parabolic FM wave packet in the length-inhomogeneous amplifier and describe the conditions for their stable (self-similar) propagation in a form of the similariton wave packet.

Thus, in the present paper, we will obtain the conditions for appearance of stable parabolic pulses in the optical fibers with W-profile of radial propagation of the refractive index in the normal group velocity dispersion region. The relation for the GVD profile describing an optimally fast FM parabolic pulse amplification will be offered. It will be shown, that the use of length-inhomogeneous FM similaritons (resistant to the wave instability) with the increasing normal group-velocity dispersion allows to produce fiber laser systems with a high peak power P>100 kW.

8434-53, Poster Session

Rectangular similaritons in fiber amplifiers and ring lasers

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Self-similarity is a fundamental physical property that has been studied in many areas of physics and, in particular, in optics.

In addition, recent studies in nonlinear optics reveal an important sort of optical pulses (similaritons) with a parabolic profiles of power and linear frequency chirps that propagate in nonlinear optical fibers with normal second-order group-velocity dispersion [1] and in optical fiber amplifiers with constant and distributed gain functions [2,3]. The propagating pulses in optical fiber amplifiers with normal dispersion are asymptotically self-similar and their asymptotic behavior depends only on the input energy. This remarkable property is connected with a global attractor which implicates the pulses with different initial conditions to the same self-similar structurally stable asymptotic [4,5].

We present here new analytical similariton solution of the generalized nonlinear Schrodinger equation (NLSE) for rectangular pulses propagating in fiber amplifier and ring lasers. We have also found kink and antikink solutions of the generalized NLSE with linear chirp. The numerical simulations confirm that these analytical solutions describing linearly chirped rectangular similaritons and kink-antikink pulses are very accurate. We anticipate that these new type similaritons can find applications in fiber amplifier systems and all fiber ring lasers.

[1] D. Anderson, M. Desaix, M. Karlsson, M. Lisak and M. L. Quiroga-Teixeiro, J. Opt. Soc. Am. B 10, 1185 (1993).

[2] M. E. Fermann, V. I. Kruglov, B. C. Thomson, J. M. Dudley, and J. D. Harvey, Phys. Rev. Lett. 84, 6010 (2000).

[3] V. I. Kruglov, A. C. Peacock, J. D. Harvey, and J. M. Dudley, J. Opt. Soc. Am. B 19, 461 (2002).

[4] V. I. Kruglov, and J. D. Harvey, J. Opt. Soc. Am. B 23, 2541 (2006).

[5] J. M. Dudley, C. Finot, G. Millot, and D. J. Richardson, Nat. Phys. 3, 597 (2007).

8434-54, Poster Session

Third-order optical nonlinearities of Ag nanoparticles fabricated by two-step ion exchange

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Silver and other metal nanoparticles are known to possess high third-order optical nonlinearities and composite materials including such nanoparticles have potential for use in integrated-optical devices.

Nonlinear effects are known to be enhanced close to optical resonances. These resonances depend on the size, shape, mutual ordering and dielectric environment of the nanoparticles. Silver nanoparticles have mostly been studied in the near-resonant regime ($lambda$ = 400-600 nm). For near-resonant excitation, the nonlinear refractive index has been demonstrated to be large, and to have a negative sign. Moreover, the silver particles have been shown to exhibit saturable absorption. Both of these properties are very interesting from device point of view. There are very few studies where Ag nanoparticles are excited in off-resonant regime.

Here, we present third-order optical nonlinearities of Ag nanoparticles fabricated using a new, two-step ion exchange [1] method. The nonlinearities were probed using the well-known Z-scan technique [2]. In our experiments, we use a Ti-Sapphire laser source operating at 800 nm, which is far from the resonance of the Ag nanoparticles. Both nonlinear refraction and absorption were studied using closed and open aperture configurations of the Z-scan method.

Contrary to expectations from previous studies for similar-sized nanoparticles, we observed that our nanoparticles possess relatively high and positive nonlinear refractive index. In line with previous studies we also observed saturable absorption from the silver nanoparticles. We believe that our results are related to the fabrication process, after which the particles may, in fact, be conductively coupled. This may have a crucial effect on the nonlinear optical response. On the other hand, our excitation is close to two-photon resonance of the nanostructures. We will address these hypotheses in our presentation.

[1] Y. Chen, L. Karvonen, A. Saynatjoki, C. Ye, A. Tervonen, and S. Honkanen, "Ag nanoparticles embedded in glass by two-step ion exchange and their SERS application," Opt. Mater. Express 1, 164-172, Optical Society of America (2011).

[2] M. Sheik-Bahae, A. A. Said, T. H. Wei, D. J. Hagan, and E. W. Van Stryland, "Sensitive measurement of optical nonlinearities using a single beam," IEEE J. Quantum Electron. 26, 760-769 (1990).

8434-55, Poster Session

Cherenkov-type second- and third-harmonic generation in random quadratic media

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Recently, nonlinear parametric processes via Cherenkov-type phase-matching in nonlinear photonic crystals, in which the nonlinearity chi^{(2)} is spatially modulated, have attracted increasing interest, in periodic, quasi-periodic, as well as random media [1]. In Cherenkov configuration coherent harmonic waves at new frequencies are emitted on a cone under certain angles ruled by the longitudinal phase-matching [2,3]. In this contribution, we study the characteristics of Cherenkov second-and third-harmonic generation in multi-domain strontium barium niobate (SBN) crystals by femtosecond laser pulses [4,5]. We analyze numerically and experimentally the effect of the shape and size of the individual ferroelectric domains on the spatial intensity distribution of the SH and TH rings. For this, we influence the ferroelectric domain distribution by applying an external electric field, leading to significant changes in size of the domains [6]. These size changes result in a strong intensity modulation of the Cherenkov ring, corresponding to the crystal symmetry 4mm. Furthermore, this modulation is also combined with an enhancement of the conversion efficiency, because of the size dependency of such type of harmonics generation. In this context, we also demonstrate the role of the polarization of the interacting waves. Because of the polarization properties of the chi^{(2)} tensor of SBN crystals, no effect of the polarization on the SH ring is observable.
In contrast, the TH intensity distribution experiences an additional modulation characterized by the cascaded process of the sum-frequency interaction of the second-harmonic and the fundamental waves.

[1] Saltiel et al. IEEE J. Quant. Elect. 45,1465 (2009).

[2] Bravo-Abad et al. Opt. Express. 18,14202 (2010).

[3] Sheng et al. Opt. Lett. 35,1317 (2010).

[4] Ayoub et al. accepted for publication in Opt.Lett.(2011).

[5] Ayoub et al. accepted for publication in Appl.Phys.Lett.(2011).

[6] Ayoub et al. Opt. Express. 19,11340 (2011).

8434-56, Poster Session

Anderson localization of light in photonic lattices for dimensional crossover

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Anderson localization is a general wave phenomenon that applies to the transport of electromagnetic, acoustic, quantum, spin, and other waves [1]. Anderson localization of light has recently attracted much attention, both theoretically and experimentally [1-4]. It has been studied in both one-dimensional (1D) [5] and two-dimensional (2D) [6] systems with randomized lattice potentials. A competition between nonlinearity and disorder was investigated, in disordered 1D [5], and 2D photonic lattices [6] and experimentally in fiber arrays [7]. In recent years there has also been an increased interest in the study of physical systems with dimensionality crossover [8-10]. The most important question in such investigations is, when and how the system crosses over from the one- to the two-dimensional behavior.

We analyze how the systems dimensionality affects and modifies Anderson localization of light. We consider specifically differences in the localization in 1D and 2D photonic lattices, including a gradual crossover from 1D to 2D behavior. We reveal that the character of localization in the systems with different dimensionality is nontrivial, depending on both the strength of disorder and on the strength of nonlinearity in the system. While in the linear regime Anderson localization is more pronounced in the 2D lattice, in the nonlinear regime this is not the case. To observe intermediate cases between 1D and 2D photonic lattices, we start from a 2D square photonic lattice and increase gradually the lattice period along one transverse direction, keeping the period along the other direction fixed. With such lattice stretching one can gradually switch from the 2D to the 1D case. One can also investigate intermediate cases, to determine the transition of localization and quantities of interest describing localization, e.g. the effective beam width and the localization length. In such a transitional geometry, there are two different localization lengths, along the two transverse directions.

REFERENCES

[1] P. W. Anderson, Phys. Rev. 109, 1492 (1958).

[2] S. John, Phys. Rev. Lett. 53, 2169 (1984).

[3] E. Abrahams, Ed. “50 Years of Anderson Localization” (World Scientific, Singapore 2010), 597

[4] A. Lagendijk, B. Tiggelen, and D.S. Wiersma, Phys. Today 24, 50 (2009).

[5] Y. Lahini, A. Avidan, F. Pozzi, M. Sorel, R. Morandotti, D. N. Christodoulides, and Y. Silberberg, Phys. Rev. Lett. 100, 013906 (2008).

[6] T. Schwartz, G. Bartal, S. Fishman, and M. Segev, Nature 446, 52 (2007).

[7] T. Pertsch, U. Peschel, J. Kobelke, K. Schuster, H. Bartelt, S. Nolte, A. Tünnermann, and F. Lederer, Phys. Rev. Lett. 93, 053901-1 (2004).

[8] A. Szameit, Y.V. Kartashov, F. Dreisow, M. Heinrich, T. Pertsch, S. Nolte, A. Tünnermann, V. A. Vysloukh, F. Lederer, and L. Torner, Phys. Rev. Lett. 102, 063902 (2009).

[9] E. Castaño and Y. C. Lee, Chinese Journal of Physics 23, 245 (1985)

[10] Z-Q. Zhang, Q-J. Chu, W. Xue, and P. Sheng, Phys. Rev. B 42, 4613 (1990)

8434-57, Poster Session

Ultrafast temporal caustics: a new approach to femtosecond beam shaping

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Accelerating beams are the subject of an increasing interest as their properties find important applications in many fields as: all-optical manipulation, curved nonlinear optics, filamentation, manipulation of non-linear processes. Although the majority of these studies have been conducted in the spatial domain, there is a growing interest in finding and generate equivalent time-domain solutions where “non-dispersive” pulses can retain high peak intensity during propagation in dielectric media. Such non-dispersive Airy pulses with parabolic temporal acceleration have indeed already successfully generated in this way, but the natural question arises as to whether this class of pulse is a unique solution or rather just one particular example of a much wider class of non-dispersive pulse.

In this paper we answer this question by using numerical studies to show how a recent caustic based approach to non-diffracting spatial beam design can be generalized to the time domain to generate a wide range of temporally non-dispersive pulse profiles and trajectories. More specifically we use the analogy between space and time variable with respect to electromagnetic wave propagation to use our inverse-problem approach to a caustic-based description of the temporally accelerating beam. We considered a beam propagating with a desired temporal acceleration profile. By treating the acceleration profile as a caustic surface envelope of a family of tangential light rays, we solved the inverse problem allowing us to determine the appropriate dispersion law to generate such acceleration. We also consider how the control and shaping of temporal acceleration could open a path to improved control of non-linear interactions and novel applications.

8434-58, Poster Session

Surface photorefractive wave on the boundary of a photorefractive crystal covered by metal

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The processes of excitation of surface photorefractive wave on the boundary of a photorefractive crystal (PR) coated by metal are investigated. The features of light-induced scattering in the nonlinear SBN-75 crystal covered by a silver film were estimated and the surface waves at its metal-coated surface were excited. It was found that in the course of propagation of a light beam with extraordinary polarization not only the scattering effect arises in the crystal, but also the effect of self-limitation for a part of the beam, propagating in the crystal without appreciable diffraction divergence, takes place. Take into account the revealed features of fanning effect, a technique for the efficient excitation of surface waves in a PR crystal is proposed. In our experiment the efficiency of the surface wave excitation was near 30 %, which is 50 times greater than that achieved earlier in exciting nonlinear surface waves in the optical region. The images of the near and far fields for the surface wave, propagating along the PR crystal-metal interface, were investigated. It is shown that the presence of a metal on crystal surface changes the character of arising surface waves at small excitation angles. In this case we observed some peculiarities of wave field distribution, consisting in the appearance of a broadened stripe of radiation and its shift from the metal-coated surface edge. The range of incidence angles for the exciting radiation in which these specific features manifest themselves most clearly is determined. The preliminary theoretical analysis of obtained experimental results was carried out.

8434-59, Poster Session

An improved molecular design of obtaining NLO active molecular glasses using triphenyl moieties as amorphous phase formation enhancers

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To be considered as potential materials with practical use, organic compounds exhibiting nonlinear optical (NLO) activity must meet several criteria as stable amorphous phase, good optical quality, thermal and chemical resistance. Different material design architectures regarding the placement of NLO active chromophores have been applied to meet those standards: covalent boding to polymer main chain, guest-host systems, dendrimeric compounds and amorphous small-molecular organic glasses. Compared to other approaches small-molecular compounds have several advantages as relatively easy synthesis, well-defined structure, higher purity and increased concentration of active chromophore. However, clear connections between molecular glass chemical structure and material key properties often remain unclear.

The results of our previous research have revealed that incorporation of triaryl moieties into different low molecular weight chromophores can serve as easily applicable and universal way for obtaining organic glasses [1]. In given study we present improved molecular design for mentioned approach where labile C-O bonding for amorphous phase formation enhancer groups is replaced by C-C bonding. Series of molecular glasses containing different aniline based azobenzene chromophores have been synthesized using different length flexible C-C bridges as linkers for triaryl moieties. Acquired new-design materials show increased chemical and thermal sustainability as well as improved amorphous phase stability. Glass transition temperatures of materials by up to 90° C are measured. Results of quantum chemical calculations, synthesis, chemical characterization and experimentally obtained linear and nonlinear optical properties of materials in solutions and solid films will be presented.

[1] Traskovskis, K., et al., Proc. of SPIE Vol. 8113, 81130Z (2011).

8434-60, Poster Session

Numerical simulation of Bessel beam filamentation in dielectrics

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The nonlinear propagation of Bessel beams is a subject of intense current interest because they represent a novel class of non diffracting field with important applications in material processing and nonlinear optics. A particular characteristic of interest is related to the conical structure of wavevectors in the beam that allows homogeneous excitation of matter over an extended interaction length and which has been successfully used to generate high aspect ratio nanochannels in glass.

An important aspect of experimental studies of Bessel beam material interaction is that Bessel beams remain stable at intensity levels where usual Gaussian beams would suffer break-up and filamentation. However, one can still observe Bessel beam unstable filaments at very high power, but the physical mechanisms both of the stable and the unstable regimes remain unclear. In this work, we report numerical studies investigating the dynamics of Bessel beam filamentation in glass, aiming to isolate and understand the physics underlying the transition from stable to unstable filamentation. Competitive effects of plasma generation and Kerr nonlinearity are compared, and we include air/glass interface effects and the effect of obstructions. A major result that we report for the first time is the destabilizing effect of Bessel filaments by obstructions which create a large field intensity gradient.

8434-62, Poster Session

Femtosecond pulses on a circle: highly non-paraxial non-diffracting beams

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The study of optical fields that propagate in free space at high intensity over extended distances along “non-diffracting” trajectories is a field of intense current activity. Aside from the intrinsic interest in understanding the linear properties of such novel beam paths, many important applications have been identified in fields such as controlled material processing, particle trapping, and nonlinear optics. We have recently shown how the propagation of such beams can be interpreted by considering the non-diffracting path as an extremum of a caustic, and the application of this idea using concepts from classical optics theory has allowed the development of a systematic technique to generate arbitrary acceleration trajectories using a spatial light modulator to impose an appropriate phase profile onto a Gaussian beam from a laser. Current research using this technique, however, has been limited only to the paraxial small-angle regime of accelerating trajectories, but in this paper, we report the experimental generation of highly non-paraxial beams that follow an extreme case of a circular path. In particular, we show how broadband 100 fs pulses can be spatially shaped into a non-diffracting lobe of 1 μm diameter that follows the arc of a circle of 25 μm radius over approximately a full quadrant of arc. We interpret our experimental results using numerical simulations, and also demonstrate the important general result that the caustic shaping does not modify the temporal pulse duration along the trajectory, a result of much importance for nonlinear applications.

8434-63, Poster Session

Intensity sweeping in accelerating beams with arbitrary trajectories

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The characteristics of accelerating Airy beams are a subject of intense current interest because they represent a novel class of non diffracting field and because of their tremendous application potential in fields such as optical manipulation, filamentation and nonlinear optics. In this context, we have recently developed a novel approach to generate a much wider class of accelerating beams with arbitrary trajectories both in the paraxial and non paraxial regimes by associating a desired acceleration trajectory with a geometrical caustic and corresponding phase mask applied to an incident Gaussian beam. In this paper, we combine this approach with powerful techniques of Fourier optics to yield control over both the acceleration profile and the intensity distribution along the caustic.

We numerically and experimentally show how this approach allows essentially arbitrary control of the intensity along the main non-diffracting lobe of the caustic, and when coupled with femtosecond beam illumination, we show how this can lead to intensity sweeping along the caustic trajectory. We also numerically investigate the filamentary propagation of such pulses and demonstrate the existence of regimes of extreme stability.

8434-64, Poster Session

Optical patterns using vortex beams

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Nonlinear light-matter interaction can lead to complex light propagation mechanisms, transverse instabilities and self-organization in so-called optical patterns [1]. Pattern formation has been studied in single feedback configuration but also in linear or ring optical cavities, and including different nonlinear media such as liquid crystals, sodium vapors and photorefractive crystals [2].

We report here theoretically and experimentally on new results on pattern formation when the input beam is not a Gaussian beam, like in previous studies, but a vortex beam i.e. Laguerre-Gaussian beam carrying an orbital angular momentum [3]. Our system makes use of coherent coupling of counter propagating vortex beams in a photorefractive crystal with a single feedback.

The combination of phase singularity and modulation instability yields interesting new phenomena. The pattern geometry is different from the one observed with a Gaussian beam of the same intensity and moreover depends on the vortex topological charge. Moreover the vortex patterned state now exhibits a rotating dynamics around the beam center, at a time-scale that depends in a complex way on both the vortex phase dynamics and photorefractive grating dynamics. Finally the threshold for pattern formation is different from the case of a Gaussian beam and depends on the vortex topological charge. These observations are in very good qualitative agreement with our theoretical work based on coupled wave equations [4]. This work brings new light into pattern formation from non conventional light states, and addresses the question of self-organization of light carrying angular momentum, which is of great interest today in the context e.g. of optical tweezers and spatial light encryption.

[1] F. T. Arecchi et al., Physics Reports 318, 1-83 (1999).

[2] T. Honda, Opt. Lett. 18, 8 (1993).

[3] A. S. Desyatnikov et al., Progress in Optics 47 (2005).

[4] V. Caullet et al., Opt. Lett. 36, 15 (2011).

8434-65, Poster Session

Electro-optical group-velocity control in reconfigurable phase-shifted grating structures

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Slow Light and group velocity control are one of the key issues regarding next generation optical networks. Particularly it is of special interest to develop tunable delay filters within the optical C band to ensure compatibility with fiber optics [1,2]. We investigate all-optical and electro-optical tunable refractive index structures, induced in lithium niobate for the generation of room-temperature slow light at telecom frequencies. The fabricated volume-holographic gratings offer low insertion loss and narrow bandwidth selectivity whereas they are insensitive to photo-induced damage in the NIR spectral region, thus making them suitable for telecom applications. In this contribution we employ phase-shift-keying to manipulate the group-velocity properties of pulses in a one-dimensional photonic band gap with broken symmetry and additional electro-optic tuning [3]. Superluminal and subluminal pulse propagation were observed and for a single phase-defect a fourfold reduction of the lightspeed was obtained. The principle of operation is diffraction from reflection type gratings centered at 1550 nm in x-cut iron-doped lithium niobate with a phase discontinuity between at least two adjacent grating sections. The grating is pumped ordinary polarized in transmission geometry and the filter response is characterized in reflection with high temporal and spectral resolution using the modulation phase-shift method. To induce the phase-defects into the grating, a phase-only spatial light modulator is used. Depending on the length, quantity and relative phase of each grating segment, the spectrum exhibits multiple narrow transmission gaps. Up to six closely spaced delay channels were successfully demonstrated by all-optical phase-shift-keying. Moreover an additional modulator was employed to control the coupling strength yielding dynamic amplitude sampled grating superstructures [4]. This enables reconfiguration and adaptability in different spectral windows at low pump intensities comparable to thermally FBG delay lines without inducing strain on the device. The spectral characteristics are highly repeatable to allow fast control of the magnitude and phase response by an external electric field. The unique feature of this particular system is the possibility to reconfigure the band gap properties on-the-fly and therefore to switch between spectral configurations to control the relative group delay.

References

[1] J. B. Khurgin, Adv. Opt. Photon. 2, 287 (2010).

[2] G. Lenz, B. Eggleton, C. Madsen, and Slusher, IEEE Journal of Quantum Electronics 37 Issue:4, 525 (2001).

[3] W. Horn, S. Kroesen and C. Denz APL, 98, 241116 (2011)

[4] D. Janner, G. Galzerano, G. D. Valle, P. Laporta, S. Longhi, and M. Belmonte, Phys. Rev. E 72, 056605 (2005).

8434-67, Poster Session

Optical limiting in carbon black suspensions under reduced ambient pressure

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As is known, powerful pulsed laser irradiation overheats microparticles in aqueous carbon. As a consequence, vapor bubbles are formed around the particles, which is the root cause of such phenomena as optical limiting and nonlinear optical scattering. Under laser irradiation, not only the liquid around the particle evaporates, but also the material of the particle. After the irradiation, relaxation of the laser-induced changes of optical properties of the suspension takes approximately a second. With taking into consideration this mechanism of interaction of microparticles with powerful laser radiation, is seems promising to investigate the influence of ambient pressure on this interaction.

Were investigated the changes of optical transmittance of aqueous water carbon sus-pensions irradiated by Nd:YAG laser (wavelength 1064 nm, pulse duration 15 ns, power density 20 MW/cm2) at a pressure of (0,1...1) Po , where Po is the atmospheric pressure.

The laser power dependence of relative optical transmission is shown in the figure. It is seen that the reduction of pressure significantly influences on the transmission. The optical transmission decreases with the growth of the incident laser power (optical limiting), and this decrease becomes stronger at low The size of laser-induced bubbles depends on external conditions such as ambient pressure. It is plausible to suggest that at low pressure the laser-induced bubbles grow with less resistance, consequently, self-induced scattering of the laser pulse is.

In addition to optical limiting, we investigated the kinetics of optical transmission and calculated the time-dependence of effective cross-section of light scattering and bubble radius after irradiation by a powerful laser pulse.

CONCLUSIONS

First detected the influence of external pressure (0.1-1 atmospheres) at transmission an aqueous suspension of carbon microparticles in conditions of optical limiting under pulsed laser irradiation .

Found that external pressure influences kinetics of induced relaxation scattering in aqueous suspensions of carbon microparticles under pulsed laser irradiation, namely, the maximum value of cross section of induced scattering and changes attenuation curve shape.

Proposed interpretation of obtained phenomena, which formed as a basis earlier developed model of interaction of powerful laser radiation with light absorptive microparticle suspensions.

8434-68, Poster Session

Computing using delayed feedback systems: towards photonics

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Reservoir computing has recently been introduced as a new paradigm in the field of machine learning. It is based on the dynamical properties of a network of randomly connected nodes or neurons and shows to be very promising to solve complex classification problems in a computationally efficient way. The key idea is that an input generates nonlinearly transient behavior rendering transient reservoir states suitable for linear classification. Our goal is to study up to which extent systems with delay, and especially photonic systems, can be used as reservoirs.

This nonlinear transient computing based on one single nonlinear component subject to delayed feedback has been recently introduced and proven to be very successful. This simple configuration, which replaces an entire network of randomly connected nonlinear nodes with one single hardware node and a delay line, is significantly easier to implement experimentally. Instead of creating typical networks of hundreds or thousands of circuits, each one representing a node, it suffices to construct only one.

In this work, we show both numerically and experimentally, that delayed feedback systems can be used to build state of the art reservoirs and that we can achieve good performance on several benchmark tasks, such as classification problems and prediction of irregular time series. The obtained performance is similar or even better than the one found with traditional reservoir computers based on large neural networks. In a next step, optoelectronic system implementations of nonlinear transient computing would open the perspective towards extremely fast signal handling and enable the construction of photonic reservoirs in a resource-efficient way.

8434-69, Poster Session

Self-heating phase-mismatching in KGW Raman generator

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A Raman generator is a simple and efficient device to convert the pulsed pump laser wavelength to Stokes and anti-Stokes wavelengths through the well-known Stimulated Raman Scattering (SRS) process. SRS formed a basis for laser wavelength conversion to wavelengths that are not easy to generate by other mechanisms. The process of SRS in a Raman generator can be describes classically by coupled-wave equations including the pump and several orders of Stokes and anti-Stokes waves. According to this formalism, the gain of the Raman generator is proportional to the pump intensity. So, to get a high intensity one should focus the pump beam in a small spot size as possible as. The previous theoretical calculations predicted that the threshold energy decreases as the beam focusing becomes tighter. However the experimental results did not confirm the theoretical results thoroughly. In this regard we believe that the heat deposition in the Raman generator by travelling waves may induce some unforeseen effects. The impact of thermal lensing on output powers and cavity stability was investigated previously by researchers. In this work for the first time we investigated the thermally-induced phase mismatching in first order Stokes and anti-Stokes outputs. To performe this, we solved five equations including three for pump, Stokes and anti-Stokes waves and one for temperature distribution and other for thermal phase mismatching, simultaneously. The theoretical simulations applied for KGW crystal that is one of the most interesting Raman generators with high gain and damage threshold. We also studied the effect of beam polarization and beam propagation directions along three distinguished crystallographic axes. The results showed for a light propagating along the Np axis where beam encounters with the most Raman gain, the Stokes efficiency increases with increasing the injection pump power when the polarization vector directed along Nm axis, although the crystal temperature increases. We conclude that in this configuration the phase mismatching decreases with the temperature increase and so the detrimental effect of self-heating converted to a useful tool.

8434-70, Poster Session

Study on the additional surface variation of large diameter and thin-type KDP plate caused by fabrication error

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Considering the additional surface variation of the large diameter (i.e., 400×400mm2) and thin-type (i.e., 9mm) KDP plate placed with the departure angles from the horizontal plane of 45° in Inertial Confined Fusion (ICF) systems, which caused by the fabrication error of KDP plate and its mounting system. A finite element analysis model for the large diameter and thin-type KDP plate has been built up based on the experimental measurement data of surface profile and its mounting system with different types and sizes fabrication error. The influence of the fabrication error of KDP plate and its mounting system on the additional surface variation of KDP plate has been simulated and the P-V and RMS values of the surface profiles have been given. Furthermore, the additional surface variation caused by different size fabrication error of KDP plate and strip surface of the mounting system, and different types and sizes fabrication error of support surface of the mounting system have been compared and analyzed. It's shown that the fabrication error of the edges of the KDP and the fabrication error with concave shape of support surface are the main reason for causing the relatively large additional surface variation. The fabrication error of KDP plate also leads to the non-uniform deformation. The fabrication error with convex, the wavy shape of support surface, and the random fabrication error of the strip surface in the mounting system, lead to relatively small additional surface variation. The additional surface variation caused by the random fabrication error of support surface is between the former and the later.

8434-71, Poster Session

A frequency-comb-referenced singly-resonant OPO for sub-Doppler spectroscopy

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We present a singly resonant cw optical parametric oscillator (OPO), emitting more than 1 W between 2.7 and 4.2 μm, which has been directly phase-locked to a near-infrared selfreferenced optical frequency comb. The OPO is based on a periodically-poled sample of 5%-MgO-doped congruent lithium niobate, with seven different poling periods, placed in a bowtie cavity. Pump beam is delivered by a 10-W-amplified fibre laser at 1064 nm. The comb synthesizer is a fs mode-locked fibre laser referenced to the Cs primary standard via global positioning system. We estimated for the idler frequency a relative Allan deviation of ~3 × 10−12 τ−1/2 between 1 and 200 s. To test the spectral performance of such source we carried out sub-Doppler spectroscopy of ν1 band rovibrational transitions of CH3I around 3.3 μm, resolving their electronic quadrupole hyperfine structure, with a spectral resolution better than 260 kHz. Sub-Doppler profiles have been fitted by six Lorentian profile derivatives. From the fit result we determined the absolute frequency of the hyperfine components with a 50-kHzuncertainty.

8434-11, Session 3

Nonlinear plasmonics

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In this talk we will discuss principles of nanoscale nonlinear optics and various realisations of all-optical active and tuneable nanophotonic components based on plasmonic waveguides as well as plasmonic metamaterials.

8434-12, Session 3

Continuous-wave mode-locked optical parametric oscillator

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Ultrafast optical parametric oscillators (OPOs) are versatile sources of ultrashort pulses for spectral regions inaccessible to conventional mode-locked lasers. Key to the operation of such OPOs is synchronous pumping, requiring ultrafast pump lasers. Given their relatively limited availability, complexity, and high cost compared to cw pump lasers, it would be desirable to devise novel strategies to overcome the need for mode-locked lasers as pumps for ultrafast OPOs. One promising approach would be direct mode-locking of continuous-wave (cw) OPOs, recently demonstrated using acousto-optic modulation, generating stable pulses with nanosecond duration [1].

Here we report the generation of picosecond pulses using a novel mode-locking technique that combines an electro-optic phase modulator (EOM) with an anti-resonant ring (ARR) interferometer in a cw doubly resonant OPO (DRO). The ARR converts the internal phase modulation into amplitude or coupling modulation. The concept was first proposed by Siegman in the context of lasers [2]. The DRO, pumped at 532 nm by a cw laser, is based on MgO:sPPLT (grating period of 7.97 micron), and configured in a standing-wave cavity. Operating near degeneracy, the DRO generates 1050 nm (signal) and 1078 nm (idler) wavelengths. For a fixed modulation depth of 1.83 radians, careful adjustment of the cavity length and modulation frequency resulted in a stable train of 730 ps pulses at 160MHz, corresponding to a spectral width of 12nm, with an average power of 31mW. Under certain conditions, we were also able to achieve 450 ps pulses at 80MHz, with an average power of 17mW. Further, we have confirmed true mode-locked operation by verifying 4 times enhancement in second-harmonic-generation power under mode-locked operation at both 80 and 160MHz, compared to that in cw operation, for a fixed average fundamental power. The DRO performance under different modulation depths with frequency detuning, and elaborate discussion on experimental techniques and results will be presented.

References

1. J-M Melkonian, N. Forget, F. Bretenaker, C. Drag, M. Lefebvre, and E. Rosencher, “Active mode locking of continuous-wave doubly and singly resonant optical parametric oscillators,” Opt. Lett. 32, 1701-1703 (2007).

2. A. E. Siegman, “An antiresonant ring interferometer for coupled laser cavities, laser output coupling, mode locking, and cavity dumping,” IEEE J. Quantum Electron. 9, 247-250 (1973).

8434-13, Session 3

Interferometeric output coupling of a continuous-wave optical parametric oscillator

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Since the invention of laser, an important parameter characterizing the performance of any optical oscillator has been the extracted power. The conventional method relies on a partially transmitting mirror (“output coupler”), but the extraction of maximum power requires experimental evaluation of different discrete output couplers, which is expensive and time consuming.

Here, we report a new technique based on an antiresonant ring (ARR) interferometer for absolute optimization of the output power from a continuous-wave (cw) singly-resonant optical parametric oscillator (SRO). We previously demonstrated the potential of this technique in ultrafast optical oscillators [1,2], but the deployment of ARR in a cw SRO is challenging, given the negligible nonlinear gain in cw regime and additional cavity losses imposed by the ARR. On the other hand, integration of ARR as a variable output coupler in a cw SRO will combine all the advantages of the device with the flexibility to achieve maximum possible output power as well as minimize intracavity thermal effects.

We deployed a cw SRO based on 50-mm-long MgO:PPLN crystal with a grating period of 31.5 micron, pumped by Yb-fiber laser at 1064nm. An ARR was integrated into the cavity for in-situ optimization of SRO output power. By varying the beamsplitter angle (θBS), continuously-variable output coupling from 0.8% to 7.3% was achieved, resulting in an ARR optimum output coupling of ~4.6% (θBS=33º) for our cw SRO. We obtained maximum signal and idler powers of 2.8W and 3.9W, respectively, at θBS=33°. We also confirmed that the deployment of ARR in cw SRO does not degrade the beam quality. Further comparison with commercial output coupler mirrors, SRO threshold powers, and elaborate discussions on experimental results will be presented. To our knowledge, this report is the first proof-of-concept demonstration of the use of an ARR for absolute optimum output coupling in a cw optical oscillator.

References

1. A. Esteban-Martin. O. Kokabee and M. Ebrahim-Zadeh, “Optimum output coupling in optical oscillators using an antiresonant ring interferometer,” Opt. Lett. 35, 2786-2788 (2010).

2. S. Chaitanya Kumar, A. Esteban-Martin and M. Ebrahim-Zadeh, “Interferometric output coupling of ring optical oscillators,” Opt. Lett. 36, 1068-1070 (2011).

8434-14, Session 3

High-energy tunable mid-infrared picosecond optical parametric generation in CdSiP2

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Mid-infrared (mid-IR) spectral range, covering 5900-6600 nm, is of great interest for human surgery, due to simultaneous absorption by both proteins and water [1]. In the absence of conventional solid-state lasers at these wavelengths, tunable optical parametric generation (OPG) is an attractive alternative for wavelength generation beyond 6 μm.

Here we report a high-energy, single-pass, OPG based on the new nonlinear material, Cadmium Silicon Phosphide, CdSiP2 (CSP) [2]. The OPG is pumped by a laboratory designed cavity-dumped passively mode-locked, diode-pumped, Nd:YAG oscillator, providing 25 μJ pulses in 20 ps at 5 Hz [3]. The pump energy is further boosted by a flashlamp-pumped Nd:YAG amplifier to 2.5 mJ. The OPG is temperature tunable over 1263-1286 nm (23 nm) in the signal and 6153-6731 nm (578 nm) in the idler, corresponding to a total tuning range of 601 nm, covering the technologically important region for surgical applications. Using the single-pass OPG configuration, we have generated signal energy as high as 636 μJ at 1283 nm, together with an idler energy of 33 μJ at 6234 nm, for 2.1 mJ of input pump energy. This corresponds to photon conversion efficiencies of 36.5% and 9.2% for signal and idler, respectively. The signal energy remains >600 μJ over the entire tuning range and the idler energy is >25 μJ over more than 55% of the tuning range. The spectral measurements at a crystal temperature of 91ºC resulted in a signal FWHM spectral bandwidth of 10.4 nm at central wavelength of 1276 nm, and the corresponding idler spectrum has an FWHM bandwidth of 140 nm centered at 6404 nm. The generated signal pulses are measured to have duration of 24 ps. To our knowledge, this is the first demonstration of high-energy, tunable OPG in the mid-IR beyond 6 μm based on CSP.

References

1. G. Edwards, R. Logan, M. Copeland, L. Reinisch, J. Davidson, B. Johnson, R. Maciunas, M. Mendenhall, R. Ossoff, J. Tribble, J. Werkhaven and D. O'day, Nature 371, 416 (1994).

2. K. T. Zawilski, P. G. Schunemann, T. M. Pollak, D. E. Zelmon, N. C. Fernelius, and F. K. Hopkins, J. Cryst. Growth 312, 1127 (2010).

3. M. Jelínek, V. Kube ek, Laser Phys. Lett. 8, 657 (2011).

8434-15, Session 3

Subwavelength plasmonic kinks, solitons, and oscillons in arrays of nonlinear metallic nanoparticles

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Due to a strong enhancement of the field induced by the excitation of surface plasmon polaritons and increased optical nonlinearity, surface plasmons can be employed for realization of a variety of nonlinear optical effects. In particular, several nonlinear optical processes have been demonstrated in plasmonic nanostructures, e.g., optical limiting and self-phase modulation in arrays of structured nanoparticles [N.C.Panoiu and R.M.Osgood, Nano Lett. 4, 2427(2004)] or second-harmonic generation in nanostructured metal films [W.Fan et al., Nano Lett. 6, 1027 (2006); J.A.H.van Nieuwstadt et al., Phys.Rev.Lett. 97, 146102(2006)]. In addition, strong geometrical confinement can boost the efficiency of nonlinear optical effects, including the generation of subwavelength solitons in metal-dielectric multilayers and arrays of metal nanowires [see, e.g., Y. Liu et al., Phys. Rev. Lett. 99, 153901 (2007); F. Ye et al., Phys. Rev. Lett. 104, 106802 (2010)]. The solitons supported by such media result from a balance between tunneling of surface plasmon modes and nonlinear self-trapping.

In our work, we suggest and study a novel class of nonlinear effects in arrays of subwavelength metallic nanoparticles. More specifically, we focus on two fundamental nonlinear phenomena: (i) bistability and (ii) modulational instability. We demonstrate that a bistable nonlinear response of each nanoparticle in the array can lead to the formation of a novel type of nonlinear localized modes---plasmonic kinks, which describe switching waves connecting two different states of polarization of metallic nanoparticles. Such plasmonic kinks are characterized by a subwavelength extent and tunable (changing from zero to a finite value) velocity. Moreover, two slowly moving kinks of the opposite polarity are able to create a stable bound state which can be regarded as a deeply subwavelength dissipative plasmon soliton.

We also analyze modulational instability in such nanostructures, and describe numerically several scenarios of its development. We show that modulational instability can result in the generation of regular periodic or quasi-periodic modulations of the particle polarizations, and reveal that the arrays of nonlinear metallic nanoparticles can support long-lived standing and moving oscillating nonlinear localized modes which can be termed plasmon oscillons, in analogy with similar localized modes in driven granular materials and Newtonian fluids [P.Umbanhowar et al.,Nature 382, 793(1996); H.Arbelland et al.,Phys.Rev.Lett. 85, 756 (2000)].

8434-16, Session 4

Nonlinear Shannon limit and the need for new fibres

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No abstract available

8434-17, Session 4

Multi-order automatic dispersion compensation for 1.28 Terabaud signals

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We demonstrate a flexible scheme with strong integration potential for performing automatic higher-order dispersion compensation for transmission of ultra-high bandwidth Optical Time Division Multiplexed (OTDM) signals. This system allows us to successfully compensate simultaneously for second, third and fourth orders of dispersion fluctuations as well as residual dispersion for a 1.28 Tb/s single channel signal (made up of 275fs pulses).

Our dispersion compensation setup consists of a dispersion monitor, i.e. a photonic-chip-based all-optical RF-spectrum analyser with Terahertz bandwidth, and a dispersion compensator based on an LCoS spectral pulse shaper. The dispersion state is monitored from the RF spectrum of the signal by extracting a single parameter, namely the 1.28THz tone power, reflecting the quality of the signal. The addition of a dispersion bias for various orders all impair the RF spectrum by decreasing the fundamental tone power and generating side peaks. An optimization algorithm maximizing the 1.28THz tone power drives the compensator to allow for automatic dispersion compensation. We evaluated the system on a test bed consisting of a transmission link emulator made of another SPS which was used to apply custom residual dispersion as well as temporal fluctuations.

Efficient simultaneous cancellation of the second, third and fourth orders of dispersion based on a single objective parameter involves a robust and fast scalar optimization algorithm for tuning all three variables eliminating the need to monitor separately the three orders of dispersion.

We show that the device, inserted anywhere in the transmission line is able to track dispersion fluctuations and recover in real time even from sharp discrete dispersion changes (worst case scenario). This work is a key requirement for the practical viability of optical transmission based on OTDM, as ultra-short light pulses become extremely sensitive to dispersion variations, due e.g. to temperature fluctuations.

8434-18, Session 4

RF-pilot-based nonlinearity compensation in frequency domain for CO-OFDM transmission

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Coherent Optical Orthogonal Frequency-Division Multiplexing (CO-OFDM) is a promising technology for optical long-haul system because of its tolerance towards chromatic dispersion (CD) and polarization-mode dispersion (PMD). OFDM modulation has however a specifically high peak to average power rations (PAPR) compared to a signal carrier modulation. Therefore the fiber nonlinearity effects such as self-phase modulation (SPM) and cross-phase modulation (XPM) is a major concern. To mitigate the nonlinearity effects, several methods have been proposed to reduce the PAPR of the OFDM system. Nevertheless, the PAPR reduction in high-rate becomes unsuitable because the cumulated chromatic dispersion in such system causing fast walk-off between subcarriers. In this paper, we investigate the use of RF-Pilot (RFP) based nonlinearity compensation in frequency domain to compensate of SPM and XPM in a high-rate coherent OFDM optical system. It shows that the RFP-based compensation has superiority over a conventional pilot-based compensation at FEC threshold.

In this technique, a pilot tone is placed in the middle of the transmitted OFDM signal which called RFP. An easy way to insert the RFP is by turn off the first OFDM subcarrier and setting a DC offset by driving the Vbias at the IQ-modulator. This RFP is affected by the SPM and XPM in a

similar way as the OFDM subcarriers. At the receiver, the compensation is done in frequency domain by inverting the RFP and multiplying it by the OFDM symbol. This can significantly mitigate the fiber nonlinearity induced by SPM and XPM. Improvement of 1.75 dBm is achieved at FEC threshold when using 256 FFT size compared to the conventional pilot-based compensation. Additionally, the optimum power of RFP for different FFT size is also revealed. It can be defined as pilot-to-signal ration (PSR). It has been obtained that PSR of -6.1 dB, -4.4 dB reflected the best performance for 256, 1024 FFT size respectively. This PSR has a major influence on the compensation performance. It can be declared that when the PSR is above the optimum value, the RFP power is too high causing the power of the OFDM signal become too low and lead to worse performance. While for low PSR, the RFP power is too low and the ASE noise affects the performance of the RFP compensation because the RFP becomes too noisy to compensate the nonlinearity effects.

8434-19, Session 4

Limits of the two-level approximation in nonlinear optics

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In the calculation of nonlinear optical susceptibilities, commonly implemented formulas require the evaluation of sums over electronic states. For molecular systems of any reasonable complexity, all but the ground state and one excited state are frequently excluded from the state summations, for reasons of simplicity. Calculations performed with this two-level approximation are widely considered to offer useful physical insights into the properties responsible for generating optical nonlinearity; certainly, for any system that can be justifiably modelled as comprising two energy levels, it affords numerous advantages. However, its application requires considerable caution: the two-level model can deliver potentially misleading results if it is applied without due regard to the essential criteria for its validity. In a series of recent works, analytical results regarding the general unsuitability of the two-level approximation have been established, and ab initio computations of hyperpolarizability for a class of merocyanine dyes have dramatically illustrated inaccuracies resulting from the exclusion of higher energy levels. This paper reports the latest results of our work on testing the validity of two-level calculations in nonlinear optics, constructed with a precise quantum electrodynamical framework as a basis for the theory. The new results show that for linear polarizability, terms associated with the inclusion of successively higher energy levels contribute progressively less to the value of the tensorial components - thus guaranteeing the sought convergence. In contrast, the values of most experimentally significant higher-order optical susceptibilities, similarly calculated, produce results that challenge the assumption of convergence.

8434-20, Session 4

Propagation of pulsating, erupting, and creeping solitons in the presence of higher order effects

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Various forms of the complex Ginzburg-Landau equation (CGLE) and solitary-pulse solutions to them is a topic that has been attracting a great deal of attention [1]. In optics, the CGLE describes a diversity of systems, namely laser systems [2] and soliton transmission lines [3]. Among its numerical solutions, we may refer the plain pulsating, the erupting, and the creeping solitons [4]. The erupting soliton was also found experimentally, in passively mode-locked solid state lasers [5].

The influence of higher-order effects, namely, intrapulse Raman scattering (IRS), self-steepening (SST) and third-order dispersion (TOD), on the above mentioned pulses have been also investigated recently [6-10]. It has been observed that IRS and SST can dramatically change the periodic behaviour of such pulses [6]. In particular, it was shown that both the pulsating and creeping solitons can achieve a fixed-shape under the influence of TOD only [7]. More recently, it has been shown that the explosions of an erupting soliton can be completely eliminated under the simultaneous action of IRS, TOD, and SST [8,9]. In some cases, the same effect can be achieved under the influence of IRS only [8,9]. Moreover, it has been found that, not only the erupting solitons, but also the pulsating and the creeping solitons can be transformed into fixed-shape pulses under the simultaneous influence of the three higher effects, [10].

In this paper we investigate numerically the dynamics of pulsating, erupting and creeping soliton solutions of the CGLE under the simultaneous influence of the third-order dispersion, intrapulse Raman scattering and self-steepening effects. The impact of these effects is considered both in the temporal and in the spectral domains. We investigate also the interaction between the above pulses, considering several situations concerning the separation and the phase difference between them. Some particular interesting cases are discussed concerning the combined action of the three higher-order effects.

[1] Akhmediev, A. Ankiewicz, (Eds) [Dissipative Solitons], Springer-Verlag, Berlin Heidelberg, (2005). [2] J.D. Moores, Opt. Commun, 96, 65, (1993).

[3] L.F. Mollenauer, J.P. Gordon, and S. G. Evangelides, Opt. Lett., 17, 1575-1577, (1992).

[4] J. Soto-Crespo, N. Akhmediev, and A. Ankiewicz, Phys. Rev. Lett., 85, nº 14, 2937, (2000).

[5] Cundiff, S., Soto-Crespo, J., and Akhmediev, N., Phys. Rev. Lett., 88, nº, 073903, (2002).

[6] H. Tian, Z. Li, J. Tian, G. Zhou, J. Zl, Applied Physics B-Lasers and Optics, 78, 199, (2004).

[7] L. Song, L. Li, Z. Li, G. Zhou, Optics Communications, 249, 301, (2005).

[8] S. Latas and M. Ferreira, Optics Lett., nº35, 11, 1771-1773 (2010).

[9] M. Facao, M. I. Carvalho, S. C. Latas, and M. F. Ferreira, Phys. Lett. A 374 (48), 4844,(2010).

[10] S. C. Latas, M. F. Ferreira and M. V. Facao , Applied Physics B-Lasers and Optics,104 ,1, 131(2011)

8434-21, Session 5

Novel frontier in integrated nonlinear optics: on-chip frequency conversion

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Up to date, the world of electronics has always been an inexhaustible source of resources to satisfy the continuous request for larger bandwidth in communication systems. Unfortunately the bit rate limit of electronic devices (around 50 Gb/s) will soon be reached, and scientists and engineers are now struggling for alternative solutions. Among them, all-optical signal processing appears to be one of the most viable since it brings the promise to drastically increase the performances of transmission networks and, at the same time, to keep the associated costs low. However, in order to fulfill the goal of realizing all-optical agile communications systems and improve overall all-optical devices performances, it is mandatory to optimally perform fundamental network operations such as optical switching, data storage, ultrafast modulation, all-optical pulse characterization etc. In particular, wavelength conversion is required, i.e., to realize wavelength division multiplexing systems capable of substantially increasing the bit rate by channeling the information on different frequency carriers, or to create all-optical oscilloscopes based on second and third order nonlinear phenomena. Recently ultra-low CW pump power (5mW) wavelength conversion based on Four Wave Mixing (FWM) has been reported in silicon micro-ring resonators. Nevertheless, it is of paramount importance

to study other material systems, since silicon is well known to suffer from two-photon absorption (TPA) that in turn induces free carrier losses and may affect the performance of silicon based devices, at least for certain applications. In this work we first demonstrated, by means of C-MOS compatible Hydex ® glass based micro ring resonators and spiral waveguides, efficient wavelength conversion by FWM using ultra-low continuous-wave pump powers. In particular, we succeeded in realizing a fully integrated, CMOS compatible, multiple wavelength source. We achieve CW optical “hyper-parametric” oscillation in a high quality factor (Q=1.2 million) as well as stable laser pulsed emission of subpicosecond pulses at repetition rates of 200 GHz and beyond.

Furthermore, we have recently shown that the same platform can be used to design integrated SPIDER devices capable to characterize pulses with a time bandwidth product up to 100. The low loss, design flexibility, and CMOS compatibility of our devices will enable multiple wavelength sources for telecommunications, computing, sensing, metrology and other areas.

8434-22, Session 5

An SMS fiber structure based on chalcogenide and silica fibers

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Recently, multimode interference occurring in a single-mode-multimode-single-mode (SMS) fiber structure (or single-mode-multimode fiber structure) has been studied for applications in novel optical devices, e.g., displacement sensor, stain sensor, temperature sensor, fiber lens, refractometer sensor and edge filter for wavelength measurements. These optical devices, based on such an SMS fiber structure, offer all-fiber solutions for optical communications and optical sensing with the advantages of ease of packaging and connection to optical fiber system. Chalcogenides are rapidly establishing themselves as technologically superior materials for emerging applications in non-volatile memory and high speed switching and have been considered for a range of other optoelectronic technologies. Chalcogenide glasses offer a wealth of active properties such as exceptionally high nonlinearity, photosensitivity, ultrafast nonlinear response and the possibility to form detectors, lasers and amplifiers.

In this paper, we present an investigation of the light propagation within an SMS fiber structure based on chalcogenide and silica fibers, which has not been addressed so far in the literature. The chalcogenide fibre based multimode interference device is fabricated and packaged by using UV curing. Due to the photo-induced refractive index changes in the chalcogenide glass material, the spectral response achieved for multimode interference also varies with both power and irradiation position for a localized laser irradiation with a max output power of 50 mW at a wavelength of 405 nm. The peak shift of the spectral responses of 1.7 nm has been realizedand we also achieved a power variation at 1550 nm as high as 2.5 dB depending on different localized laser irradiation positions along the chalcogenide fibre. The fabricated device offers the potential for low-cost, robustly assembled fully integrated all-optical switching and tunable filter devices due to its unique high nonlinearity and ease of fabrication.

8434-23, Session 5

Photonic chip based tunable slow and fast light via stimulated Brillouin scattering

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We report the first demonstration of photonic chip based tunable slow and fast light via stimulated Brillouin scattering. Slow (~ 2307 km/s) , fast and negative (~ -6818 km/s) group velocities were observed in a 7 cm long chalcogenide (As_2S_3) rib waveguide with group index change ranging from ~ -44 to +130, which results in a maximum delay of ~ 23 ns at a relatively low pump power of ~ 300 mW. Demonstration of large tunable delays in a chip scale device opens up applications such as frequency sensing and true-time delay for phased array antenna where integration and delays ~ 10 ns are highly desirable.

8434-24, Session 5

Four wave mixing in silicon hybrid micro photonic structures

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Electronic nonlinearities can be used to switch refractive indices ultra-fast well within the duration of an optical pulse. This dynamic refractive index shift can be used to shift wavelengths as well as to mix pulses of different center wavelengths. Due to its high refractive index silicon is suitable for tightly focusing light and generating high intensities required for such nonlinear effects, however high nonlinear losses in silicon (two photon absorption and absorption by free carriers generated via two photon absorption) limit transmission of high power pulses in silicon. Polymers and chalcogenide glasses don’t show free carrier absorption and also have an improved nonlinear figure of merit.

Due to acceptable levels of losses from generated free carriers, silicon organic or silicon glass hybrid structures offer to achieve high conversion efficiencies and large net gain in micro photonic devices, which can be used for the generation of entangled photon pairs, parametric amplification and parametric oscillators. We show both theoretical estimates and experimental results for four wave mixing conversion efficiencies in silicon hybrid structures.

8434-25, Session 5

Self-trapped beams for fabrication of optofluidic chip

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Self-written waveguides possess unique characteristics that can be strongly beneficial for the fabrication of integrated optical devices. Low loss waveguides induced by self-trapped beams can be formed in the heart of bulk media. Moreover, such waveguides are intrinsically optimized due to their self-adapted nature. As an emblematic demonstration we show that self-trapped beam can write waveguides crossing channels engraved in a monolithic wafer. The configuration is developed to realize compact optofluidic devices [1] to assess properties of liquids present in channels.

Waveguides and channels are built together in a photonic grade congruent $LiNbO_3$ substrate. A precision saw equipped with a polishing blade is employed to fabricate typical 100µm deep channels. Photorefractive nonlinearity controlled by the pyroelectric effect [2] is used to induce the beam self-focusing effect. Self-trapped beams are obtained at visible wavelength using a homogeneous temperature raise of the $LiNbO_3$ wafer of about 20°C for a few minutes. They can form even when light intersects 200µm wide channels at large angle of incidence. After the writing phase robust index change is present in $LiNbO_3$ constituting two waveguides located on both sides of the crossed channel. The two waveguides are automatically and perfectly aligned to each other. This feature is employed to design optofluidic sensors, difficult to fabricate or unachievable using standard techniques. The potential of this versatile technique, based on beam self-trapping, opens up new possibilities to realize innovative arrangements of precisely

aligned waveguides.

[1]-D. Psaltis, S. R. Quake, C. Yang, “Developing optofluidic technology through the fusion of microfluidics and optics”, Nature, 442, 381-386, (2006).

[2]-J. Safioui, F. Devaux, M. Chauvet, « Pyroliton: pyroelectric spatial soliton », Opt. Expr., 17, 22209, (2009)

8434-26, Session 6

Filamentation-free femtosecond plasma dynamics in hollow core fiber

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No abstract available

8434-27, Session 6

Nonlinear propagation and filamentation of intense Airy beams in transparent media

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Ultrashort laser pulse filamentation attracted growing attention since 1995 [1]. Numerous investigations uncovered a rich physics with competing nonlinearities, leading to various interpretations of spectacular phenomena such as conical emission or nonlinear propagation over long distances [2]. Of particular importance is the spontaneous reshaping of the pulse into nonlinear conical waves, then acting as attractors for the filamentation dynamics [3,4]. We investigated the nonlinear propagation of ultrashort laser pulses when the beam is preliminarly reshaped into an Airy beam.

First, we analytically demonstrate the existence of stationary nonlinear Airy beams sustained by a balance between diffraction, third-order (Kerr) nonlinearity and nonlinear losses, in one transverse dimension. Numerical simulations and experiments, in agreement with the analytical model, highlight how these stationary solutions sustain the nonlinear evolution of Airy beams [5]. Second, we investigate the nonlinear dynamics of the two-dimensional counterparts of these intense Airy beams in Kerr ionizing media, from numerical simulations and experiments. We analyze in depth the effects of initial Airy lobe size, power and size of the truncating diaphragm. Our analysis shows two distinct nonlinear propagation regimes: (i) A regime of stationary propagation, which preserves the transverse acceleration of the Airy peak, for powers in the main Airy lobe below a certain threshold. Stationary propagation is sustained by a continuous energy flux to the main Airy lobe from it neighbors, similarly to the mechanism sustaining nonlinear Bessel beam propagation. (ii) Airy beams with higher powers in the main lobe reshape into a multifilamentary pattern induced by Kerr and multiphoton nonlinearities. The nucleation of new filaments and their interaction, affects the acceleration of the main Airy lobes. We show that the size of the truncation constitutes a control parameter for the energy flux that features the Airy beam acceleration. Experiments performed in water corroborate the existence of these two regimes.

1. A. Braun et. al., Opt. Lett. 20, 73 (1995).

2. A. Couairon and A. Mysyrowicz, Phys. Rep. 441, 47 (2007).

3. D. Faccio et al. Opt. Express 16, 1565 (2008).

4. P. Polesana et al., Phys. Rev. Lett 99, 223902 (2007).

5. A. Lotti et al., Phys. Rev. A 84, 021807 (2011).

8434-28, Session 6

Effect of lens tilt on SCE and filamentation from tightly focused fs pulses in air

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Controlling of multiple filaments during the long range propagation of high power fs pulses has been a major challenge for various applications, which was solved by tilting the focusing lens effectively controlling number, pattern and spatial stability of filaments [1]. The supercontinuum emission (SCE) associated with the filaments due to tilted lens was observed to reduce with increased tilt of the lens for loose focusing geometries with focal length, f > 100 cm [2].

We present the experimental results on the SCE evolution associated with filaments due to the tilt of the focusing lens under tight focusing geometries (f < 12 cm). Transform limited fs pulses (800 nm, 45 fs, 1 kHz rep. rate) are focused in air using three different focusing geometries f/#6, f/#7.5 and f/#12 corresponding to numerical apertures (NA) of 0.04, 0.06 and 0.08, respectively. The focusing lens was tilted from zero up to 20 degrees. The filaments decayed into two shorter parts by tilting the lens and the separation between the shorter filaments has increased with increasing lens tilt, in tune with earlier reports [2]. However, the SCE spectra have shown an anomalous behavior. Though the SCE suppresses at larger tilt angles of 12 - 20 degree, at lower tilt angles up to 8 degrees the SCE is same as that observed without any tilt. This behavior is predominant with tighter focusing geometries of f/#6 and f/#7.5. Systematic study of the lens tilting effect on anomalous SCE spectra and filament characteristics in the tight focusing geometry will be presented.

1. G. Fibich, S. Eisenmann, B. Ilan, A. Zigler, Opt. Lett. 29 (2004) 1772 - 1774.

2. Y. Kamali, Q. Sun, J.-F. Daigle, A. Azarm, J. Bernhardt, S.L. Chin, Opt. Commun., 282 (2009) 950-954.

8434-29, Session 6

Filamentation characteristics of sharply focused fs pulses in atmosphere

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From the initial observation of self-channeling of high-peak power femtosecond (fs) laser pulses in air by Braun et. al. [1], propagation of intense ultrashort laser pulses in air has been one of the most exciting fields of nonlinear optics. When the transverse power of the propagating fs pulse is higher than the critical power for self-focusing (PCr) of the medium, a dynamic structure with an intense core propagates over extended distances much larger than the typical diffraction length while keeping a narrow beam size without the help of any external guiding mechanism, known as filament occurs [2].

We present the experimental investigations on the evolution filament characteristics of sharply focused fs pulses (800 nm, 45 fs, 1 kHz) pulses in air. Pulses with input powers in 3 - 12 PCr range were focused in three different focusing geometries f/#10, f/#15 and f/#20 corresponding to numerical apertures (NA) of 0.05, 0.033 and 0.025, respectively. The dynamics of the filaments were observed via direct imaging of the entire reaction zone. The length of the filament has decreased with increasing NA from 0.025 to 0.05, while, the filament width has increased. For a given focusing geometry, the filament length and width increased with increasing power, however with higher NA, the length and width were observed to saturate. With the highest NA of 0.05(f#10) and higher input

powers used in the current study, the presence of coherently interacting multiple filaments either resulting in a fusion or exchange of power is observed in cognizance with the phenomenon observed with unfocused or loosely pre-focused fs pulses propagating in air [3].

1. A. Braun et. al., Opt. Lett. 20, 73 (1995).

2. A. Couairon and A. Mysyrowicz, Phys. Rep. 441, 47 (2007).

3. P. P. Kiran et. al., Phys. Rev. A, 82, 013805 (2010).

8434-30, Session 6

Detection and analysis of low-frequency electromagnetic emissions from ns laser induced breakdown of air

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The low frequency electromagnetic emissions, ranging from radiofrequency (RF) to terahertz (THz), from laser produced plasma have become one of the most significant areas of research due to their wide range of applications [1-3]. We present the results on the electromagnetic (em) spectrum emitted in the 70 MHz - 1 GHz frequency range from the laser induced breakdown of atmospheric air. Laser pulses (7 ns) from second harmonic of an Nd:YAG laser (532 nm) were used to breakdown atmospheric air to form plasma. In this process, the electrons and ions get expanded away from the centre of the plasma with different speeds due to the difference in their masses resulting in the local charge separation. Thus dipole moment is induced in the homonuclear molecules of nitrogen and oxygen (the main components of atmospheric air), which naturally have no permanent electron dipole moments [4,5]. The RF region originating from the longitudinal oscillation of these induced dipoles from the laser induced plasma was detected using the broadband Diamond antenna (RH-799, 70 MHz to 1 GHz). A spectrum analyzer (Agilent PSA E444A, 3 Hz to 50 GHz) was used to monitor and record the RF spectrum from plasma. In addition to the resonant frequency of the antenna many other frequency lines were observed. By tuning the length of the antenna, lines corresponding to the different resonant frequency were observed at different laser energies. The amplitude of these lines has reduced with increasing laser energy beyond 50 mJ. The total emitted RF energy has also increased with increasing laser energy up to 50 mJ, beyond which almost no emission is observed in the detection range. This was observed due to the presence of multiple breakdown sources due to the self-focusing of the ns laser pulses, leading to higher collisions between the plasma electrons and eventually reducing the induced dipole moment. The emitted radiation showed a specific polarization property associated with the input em radiation. From the nature of the observed energy level transitions, the properties of the material (solid, gas, liquid state) in an excited/ionized state can be understood.

References:

1. Hirotomo Nakajima, Yoshinori Shimada, Toshihiro Somekawa, Masayuki Fujitha and Kazuo A. Tanaka “Nondestructive sensor using microwaves from laser plasma by sub nanosecond laser pulses” IEEE Geoscience and Remote Sensing Leters, Vol 6, No.4 (2009).

2. Hirotomo Nakajima, Michiteru Yamaura,Yoshinori Shimada, Masayuki Fujitha and Kazuo A. Tanaka “Ground penetrating radar using a microwave radiated laser induced plasma” Journal of Physics: Conference series 112, 042086 (2008).

3. Yao-Chun Shen, “Terahertz pulsed spectroscopy and imaging for pharmaceutical applications: A Review”, International Journal of Pharmaceutics 417,48- 60 (2011).

4. C.N.Banwell and E.M.McCash, “Fundamentals of Molecular Spectroscopy” fourth edition, 1994.

5. D. V. Kartashov, A. V. Kirsanov, A. M. Kiselev, and A. N. Stepanov, “Nonlinear absorption of intense femtosecond laser radiation in air”, Optics Express 7552, 14(17) (2006).

8434-31, Session 7

Nonlinear optics in telecommunications

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No abstract available

8434-32, Session 7

Light-by-light polarization control and stabilization in optical fibers for telecommunication applications

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With the advent of future transparent ultra high-bit rate capacity transmission networks, encoding the data would necessary involve all the physical parameters of a light beam, including multi-level in intensity, phase, polarization and even propagation modes. These complex optical fields will then naturally suffer from strong impairments imposed by linear and nonlinear propagation effects. Hence, developing new all-optical tools able to control or regenerate any properties of light has become of a crucial interest.

In this work, we experimentally report that it is possible, using a unique segment of optical fiber, to all-optically manipulate and regenerate both the state of polarization (SOP) and intensity profile of a 40-Gbit/s Return-to-Zero telecommunication signal. Based on Kerr effect taking place in a single fiber, this dual polarization/intensity regenerator is based on a polarization attractor coupled to a Mamyshev reshaper. The polarization attraction is based on a four-wave mixing interaction between an arbitrary polarized signal wave and a counter-propagating pump with a fixed SOP. Whatever the state of polarization at the input of the device, the attraction process traps and stabilizes the output SOP to a unique state without any polarization dependent loss. On the other hand, the strong nonlinear regime of propagation occurring in the polarization attractor coupled to normal chromatic dispersion of its fiber provides a large intensity dependent spectral broadening. This phenomenon can then be used to reshape the intensity profile of the signal by means of the offset filtering method initially proposed by Mamyshev. This new class of device, enabling both all-optical polarization and intensity profile control constitutes a new kind of 3R signal processing, namely Repolarisation, Reamplification and Reshaping.

Finally, we will report for the first time significant recent results dealing with a new pump-free configuration, which give rise to a much simple and easy to implement promising device.

8434-33, Session 7

Fiber-based astronomical optical frequency comb with optical feedback

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The generation of a broadband optical frequency comb with 80 and 160GHz spacing by propagation of a sinusoidal wave through three optimized nonlinear fibres is numerically investigated. The input power, the dispersion, nonlinearities, and lengths are optimized for the first two fibre sections for the generation of low-noise ultra-short pulses. The final stage is a low-dispersion highly-nonlinear fibre where, the ultra-short pulses undergo self-phase modulation for strong spectral broadening. The modeling is performed using a Generalized Nonlinear Schrodinger Equation incorporating Raman and Kerr nonlinearities, self-steepening, high-order dispersion and gain.

In the proposed approach the sinusoidal input is molded in the first

fibre section. This is shown to be necessary to minimize noise buildup during the high-order soliton fission, when the pulses are subsequently amplified in the next fibre section which is a rare-earth doped-fibre with anomalous dispersion. We demonstrate, that there is an optimum balance between dispersion and input power×nonlinearities to have adiabatic pulse compression and minimization of the noise buildup in both fibres. It is shown that the intensity noise grows exponentially as the pulses start to be compressed in the amplifying fibre. Eventually, the noise decreases and reaches a minimum when the pulses are maximally compressed. A train of 70fs pulses and 5kW peak power with negligible noise are generated, which can be spectrally broadened in highly-nonlinear fibres. The main drawback of this compression technique is the small fibre length tolerance where noise is negligible (smaller than 10 cm for erbium-doped fibre length of 15 m). The coherence of the comb is investigated via cross-correlation calculations for all-normal dispersion fibres and fibres with zero-dispersion near the central comb wavelength. The comb coherence is finally modified by incorporating a feedback loop to obtain a highly-coherent frequency comb appropriate for calibration of astronomical spectrographs.

8434-34, Session 7

Toward Mid-IR supercontinuum generation in bismuth-lead-galate glass based photonic crystal fibers

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The use of broadband mid infrared (mid-IR) sources in the fields of sensing and spectroscopy has seen a tremendous increase in recent years. Several promising MidIR optical glasses, such as the selenide and sulphide glasses, crystallize easily during the thermal handling undergone as part of the fiber drawing process, as well as darkening during exposure to high power laser pulses and being toxic due to the dopants used to enhance the nonlinearities. Therefore, from the point of view of both the manufacture and the subsequent deployment of the fiber in a biosciences application, the use of the tellurite and heavy metal oxide glasses bestows a significant advantage.

In this paper we report a two octave spanning supercontinuum generation in the range 750 - 3000 nm with a newly developed photonic crystal fiber. The fibre is fabricated using an in-house synthesized lead-bismuth-galate glass PBG08 with optimised rheological and transmission properties in the range 500 - 4800 nm. The photonic cladding consists of 8 rings of air holes with a fibre core diameter of 3 µm and a lattice constant of 2.2 µm. The dispersion characteristic is determined mainly by the material dispersion and the first ring of holes in the cladding with a filling factor of 0.68. The filling factor of the remaining 7 rings is 0.45 which allows single mode performance of the fibre in the infrared range. The fibre has a zero dispersion wavelength of 1490 nm which allows the use of 1550 nm wavelength as an efficient pump in the anomalous dispersion regime. The 2 cm long sample of photonic crystal fiber is pumped in the femtosecond regime with a pulse energy of 10 nJ at a wavelength of 1550 nm. A flatness of 5 dB is observed in the spectral range 950 -2500 nm.

8434-35, Session 7

Application of Brillouin scattering to optical frequency combs

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Optical frequency combs are a useful tool for measuring reference laser frequency whose uncertainty depends on the stability and accuracy of the reference clock. The relative uncertainty of the laser frequency measurements in the optical telecommunication band with the frequency comb technique is estimated around 10-12.

In this paper, we present the development and implementation of a filtering technique on the optical frequency comb using Brillouin scattering amplification. This filtering technique allows us to isolate and transmit frequencies generated by a stabilized optical frequency comb. The optical frequency comb filtered, which has been previously characterized, is based on an Erbium optical fiber oscillator and it is employed to the calibration of high wavelength resolution meters in the optical telecommunications window. The characterization of the optical frequency comb and the measurements with uncertainties under the resolution of the own instrument achieved using stabilized lasers at molecular absorptions is also presented in this work. The result obtained in these measurements is a significant improvement of the measurement capability.

The method proposed has been developed for the remote comparison of frequency combs.

8434-36, Session 7

All-optical fiber-based devices for ultrafast amplitude jitter magnification

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Detecting low power fluctuations with an easy-to-implement device is of practical interest for many photonic applications such as pulse characterization or biophotonics. Several solutions have already proved their efficiency such as synchronous detection, radio-frequency analysis or autocorrelation measurements. However, they require the use of dedicated and onerous instruments. We report here two simple and efficient alternatives based on single-mode fibers and taking advantage of the nonlinear effects affecting an ultrashort pulse propagating in the anomalous regime of dispersion.

The principle of our method lies in the transfer function (TF) which links the pulse peak powers before and after the devices. If for a working power P0, this TF can be locally approximated by a linear function having a x-intercept PC with 0 < PC < 2P0 , then the relative level of amplitude jitter will be increased.

We propose and experimentally demonstrate two fiber-based schemes fulfilling this requirement. In a first configuration, we investigate the amplitude jitter of a 10-GHz picosecond pulse train at telecommunication wavelengths. Using self-phase modulation followed by an optical band-pass filtering, we show a 10 times magnification of the relative fluctuations. In a second configuration, we have focused on a femtosecond pulse train at 1033 nm propagating in a photonic crystal fiber. The resulting soliton Raman self-frequency shift followed by a long-pass optical filtering is found to be efficient to provide the required thresholding function.

In both cases, we have experimentally achieved a magnification factor above 10 and quite remarkably, we have shown that the statistical distribution of the amplitude fluctuations is maintained after magnification. The choice of the working power is crucial and for input powers which do not lie in the linear part of the TF, a strong reshaping of the statistical distribution can be observed, leading to heavily tailed statistics.

8434-37, Session 8

Silicon-based parametric frequency combs

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No abstract available

8434-38, Session 8

Continuous wave supercontinuum generation aided by a weak pulse laser

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The supercontinum generation (SC) has been achieved mainly by two different approaches, namely, with femtosecond intense pulses or using a continuous wave laser or larger pulses centered on the anomalous dispersion region. In order to improve temporal coherence, it has been suggested the introduction of a pulse seed or the propagation of both a large pulse pump and a small weaker continuous wave to control the soliton fission.

Here we propose supercontinuum generation using a hybrid input, we pump with a continuous laser and copropagate a picosecond signal. We compare the bandwidth and temporal coherence of the supercontinuum using only the continuous pump or the hybrid setup.

Simulations of the generalized Schrodinger equation, using an adequate input-noise model to reproduce the spectrum of the continuous signal, are performed in order to anticipate which dispersion regime is optimal to generate a good supercontinuum in the optical communications window.

8434-39, Session 8

Observation of modulational and hydrodynamic instabilities of multiple four-wave mixing

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The beating of two equally intense laser beams detuned by deltaf produces in an optical fiber multiple four-wave mixing (FWM) products f0 ± n.deltaf/2 (n odd integer). The overall process has been recently predicted to undergo two different instability processes. When GVD is normal and weak, a hydrodynamic type of instability leads to generation of dispersive shock waves characterized by trains of narrow dark solitons emitted in a fan which emanates beyond a singular point (shock) occurring at finite length. Viceversa in the anomalous dispersion regime the beat signal develops a novel type of modulational instability which entails the collective growth of sideband pairs equally detuned from each FWM product.

We report the experimental observation of both processes. To this aim we use distinct setups. In the shock experiment a dual frequency signal at 28 GHz is synthetized by using a LiNbO3 intensity modulator driven at its null transmission point by a half-frequency RF clock, further amplified through a EDFA, and injected in a 6-km long NZDSF (D=-2.5 ps/nm/km). The signature of dispersive shocks is observed in frequency domain in terms of significant broadening of the output spectrum, as well as in time domain where direct mapping of the output temporal profile vs. the injected power outlines the formation of the singularity and the collisions between dark soliton trains from adjacent periods of the input waveform. In the second experiment two different external cavity lasers amplified in a EDFA are employed to reach an average power of 800 mW in a 10 km long standard fiber (SMF, D=17 ps/nm/km). The onset of collective MI is witnessed by sideband pairs growing spontaneously from noise over the first three orders of FWM. By controlling the laser detuning, we also draw experimental maps of the output spectra vs. beat frequency, which exhibit interesting resonance phenomena.

8434-40, Session 8

Supercontinuum generation in the black light region by pumping at 355 nm a silica photonic crystal fiber

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Over the last few years, there have been a number of important efforts to extend the blue and UV sides of supercontinuum generation in photonic crystal fibers. These efforts are motivated by applications of broadband UV light in biomedical sciences and spectroscopy. While most of the experiments have been performed by pumping in near infrared or visible regions, it is remarkable that the use of laser emitting in the ultraviolet (UV) as pump for SC generation in PCF has not yet been endeavored.

In this work, we demonstrate that, despite both the strong absorption and large normal dispersion of silica PCF in the UV, a broadband continuum can be efficiently generated in the black-light region of the electromagnetic spectrum by pumping a silica PCF with a picosecond microchip laser emitting at 355~nm. A detailed spectral analysis shows that this UV continuum results from the interplay of multiple intermodal parametric four-wave mixing (FWM) processes and cascaded Raman scattering (CRS). We further compare this spectrum with the UV side of supercontinuum generated by an infrared microchip laser at 1064-nm. The main limitations in terms of bandwidth and power are also discussed and simple solutions are suggested for further progress.

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8435-01, Session 1

OLED lighting technology: a snapshot on features and performance

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In the past few years solid state lighting has entered the lighting market with its energy saving potentials and long operational lifetime. The new technology enables completely new ways of illumination and new intelligent lighting systems. In this regard organic light emitting diodes (OLED) are a very attractive and aesthetic form. These two-dimensional light sources are thin, lightweight, can inherently be mirror-like, potentially transparent or even flexible with completely new and nearly unlimited possibilities in future lighting applications.

This contribution will shed light on these unique features of the OLED technology and elucidate the different aspects in possible application scenarios. Furthermore the basic concepts behind OLED lighting technology will be reviewed and the recent achievements and state-of-the art performance data will be presented.

8435-02, Session 1

Recent advancements of OLED display and OLED lighting technology using the doping approach

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The optimization of charge carrier injection and transport is of crucial importance for today's and future organic electronic applications as Organic light-emitting diodes (OLEDs) and organic photovoltaic devices (OPV). Novaled has established over the last decade the intentional doping approach as one main method to lower operating voltage and increase power efficiency in OLEDs.

For OLED display applications our work has been focused in the last years on further development of charge carrier transport and doping materials to enhance the crucial blue pixel performance, especially for top emission OLEDs. With a new portfolio of electron transport materials it is possible to tune the relation between OLED lifetime (here T96 is used as measure) and the blue OLED current efficiency. This is needed due to the trade-off between long lifetime and high current efficiency commonly observed for low voltage fluorescent OLEDs (Voltage below 4,5V). With a special new ETL system up to 10times longer lifetimes can be achieved, on the cost of a little lower efficiency and increased voltage. In the EU funded project AMAZOLED we have used part of our learning's to create white top emission OLED displays for avionic applications.

Another market area for OLEDs is OLED lighting, where a maximum power efficiency is of utmost importance. Since the operating voltage of white PIN-OLEDs is already low at around 3V lately focus was given on further enhancing the out-coupling efficiency of large area flat OLEDs. By making use of a newly developed internal out-coupling organic material called NET-61 and integrating this into the n-doped electron transport system of a white triple stacked PIN-OLED, 60lm/W efficacy (at 1.000cd/m^2 and colour x,y=0,47/0,429) and 90.000hours lifetime (T50) could be achieved. This new material allows scaling of the OLED area and out-coupling effects since it can be deposited by normal large area vacuum coating technologies.

8435-03, Session 1

Solution processed multi layer OLEDs with low onset voltage

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Today, vacuum sublimed OLEDs are a mature technology with competitive device efficiencies and life-times. On the cost side, future improvements are expected to emerge from new deposition technologies such as printing and coating. Though the deposition of polymers from solution has been demonstrated in polymer light emitting diodes (PLEDs), PLEDs still exhibit a moderate performance as compared to vacuum deposited organic light emitting diodes (OLEDs) from the small molecules, since polymers have a higher molecular defect density and can be less effectively purified

In order to combine the cost advantages of solution processing with the benefits from small molecule material properties, we investigate different small molecule functional layers deposited from solution as substituent for polymers in OLEDs. The commonly used poly(3,4-et hylendioxythiophene):poly(styrenesulfonate) (PEDOT:PSS) as hole injection layer can be replaced by the p-doped small molecule material system 4,4',4"-tris(N-3-methylphenyl-N-phenyl-amino)triphenylamine / 7,7,8,8-tetracyano-2,3,5,6-tetrafluoroquinodimethane (MTDATA:F4TCNQ) without any performance losses. The introduction of an electron injection and hole blocking layer from cesiumfluoride doped bathophenanthroline (BPhen:CsF) under the cathode can be achieved by deposition from ethanol solution and leads to a significant enhancement of the OLED efficiencies as well as a reduction of the onset voltage.

By adding suitable electronically active and inactive polymers to the small molecule ink formulations we improved the layer morphologies, whereas in the absence of stabilizing polymers, thin films from small molecules tend to form aggregates and hence inhomogeneous films.

8435-04, Session 1

Influence of barrier absorption properties on laser patterning thin organic films

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This paper presents a study of selective ablation of thin organic films (LEP- Light emitting polymer, PEDOT:PSS-Hole injection layer) on various kinds of barrier foils for the development of Organic Light Emitting Diode (OLED). Different SiN barriers with dedicated absorption spectra are taken into account for this purpose.

The drive for looking into different types of SiN comes from the fact that the laser selective removal of a polymer without damaging the barrier layer is challenging in the dynamic laser processing of thin films. The barrier is solely responsible for the proper encapsulation of the OLED stack on foil. The main limitation of current OLED design is because of its shorter life span, which is directly related to the water permeation (WVTR) into the stack, leading black spots on it.

The influence of SiN absorption spectra on the selectivity of laser patterning process has been studied. To obtain a wider process window for laser patterning, the optical absorption at 248 nm for thin organic layers (LEP, PEDOT:PSS) should be as high as possible, while the absorption by the SiN for the same wavelength should be as low as possible. An optimization of laser parameters like fluence and number of shots has been done for the various types of SiN foils. The SiN damage thresholds and organic film threshold fluences are determined.

We are able to obtain a wider process window for the selective removal of LEP and PEDOT:PSS from SiN, by selection of the appropriate type of SiN. The scanning electron microscope (SEM), optical profiler (Wyko) and mechanical profiler are utilized for the detailed analysis. As part of the future work, we will assess the barrier properties after laser patterning.

8435-05, Session 1

Roll-to-roll printed simple photovoltaics on paper substrates

B. Trnovec, B. Engler, T. Zillger, M. Ali, N. Wetzold, A. C. Hübler, Technische Univ. Chemnitz (Germany)

Bulky and rigid silicon solar cells with power conversion efficiency above 10% and a lifetime of 25 years have become the benchmark in photovoltaic industry. However, there are plenty of scopes for disposable and inexpensive solar cells with a moderate efficiency and a shorter lifetime, which can be compared with plant leaves with a typical efficiency of 2-7% and a lifetime less than a year. We report a simple polymer/fullerene photovoltaic cell printed on a paper substrate. Our solar cell is free from expensive indium-tin-oxide and does not employ any vacuum process. We used only four roll-to-roll printing steps to print the complete solar cells under normal room conditions with a layer structure of paper/Zn/ZnO/PCBM:P3HT/PEDOT:PSS. Naturally oxidized zinc film, printed by transfer printing on paper, acts as cathode. ZnO nanoparticles, printed by gravure printing, acts as hole blocking layer. Photoactive layer is a bulk hetrojunction of polymer/fullerene, printed by gravure printing. Poly(3,4-ethylenedioxythiophene) poly(styrenesulfonate) (PEDOT:PSS), printed by gravure printing, acts as transparent anode. Our report demonstrates free patterning of all the four functional layers by gravure and flexographic printing techniques. The advantage of free patterning of all these layers is that it eliminates any extra process required to interconnect solar cells into a solar module. Despite the high surface roughness of paper substrate, our solar cells show power conversion efficiency in the range of 0.3 - 1.6 %. A paper substrate has several advantages, since it is inexpensive, eco-friendly, bio-degradable, easily recyclable, mechanically flexible and compatible with well-established printing processes. The solar cells can easily be recycled together with aluminum-coated food packages by the existing recycling systems. Our approach for a simple solar cell can start a new concept of use-and-throw solar cells.

8435-06, Session 2

Semiconducting polymers for transistors and solar cells

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The evolution of organic electronics is now poised to enter the commercial phase, with the recent market introduction of the first prototypes based on organic transistors fabricated from solution. Understanding the impact of both the organic semiconductor design and processing conditions, on both molecular conformation and thin film microstructure has been demonstrated to be essential in achieving the required optical and electrical properties to enable these devices. Polymeric semiconductors offer an attractive combination in terms of appropriate solution rheology for printing processes, mechanical flexibility for rollable processing and applications, but their optical and electrical performance requires further improvement in order to fulfil their potential. Organic solar cell efficiencies are currently increasing rapidly based on organic bulk heterojunction devices fabricated from solution. Central to these device efficiency improvements are the development of new photoactive semiconducting donor and acceptor materials, designed at the molecular level to optimise both absorption of the long wavelength region of the solar spectrum and generation of high cell voltages. This presentation will examine some of the key design strategies to control the molecular orbital energy levels and microstructure of donor polymer semiconductors and illustrate with examples and their characterisation. Specifically, the systematic reduction of the bandgap in a series of bridged ladder type indenofluorene1 copolymers, in combination with the progressive lowering of the HOMO energy level will be shown. Analogues of these polymers also exhibit high charge carrier mobilities, and we will present transistor data.

8435-07, Session 2

Blue light emitting Cu(I) complexes and singlet harvesting

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No abstract available

8435-09, Session 2

Molecular design of triazine derivatives having a high up-conversion efficiency from triplet into singlet excited states and their application for OLEDs

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To achieve a high exciton production efficiency at a singlet excited level (S1) in OLEDs, we employed the mechanism of thermally activated delayed fluorescence (TADF). In order to obtain a high efficiency of TADF, rather small energy gap (ΔES-T) formation between S1 and triplet excited (T1) levels should be necessary for light-emitting materials, which can be attained by small orbital overlapping between the highest occupied molecular orbital (HOMO) and the lowest unoccupied molecular orbital (LUMO). Our molecular design is to introduce a large intramolecular distortion between donor and acceptor units aimed for small ΔES-T. Based on this conception, we synthesized a new triazine derivative (CC2TA) having bicarbazole substituents. CC2TA exhibits a clear separation of HOMO and LUMO and realizes a considerably small ΔES-T of 0.06 eV. TADF was observed for CC2TA in both of the neat and a 6 wt%-CC2TA:bis(2-(diphenylphosphino)phenyl)etheroxide (DPEPO) co-deposited films under photoexcitation, which was confirmed by the fact that fluorescence and delayed fluorescence spectra of CC2TA shows exactly spectra. Fluorescence lifetime and delayed fluorescence lifetime of 6 wt%-CC2TA:DPEPO co-deposited film were 27 ns and 22 µs, respectively, at room temperature. The photoluminescence quantum yields of a CC2TA neat film and a 6 wt%-CC2TA:DPEPO co-deposited film were 43.1% and 62.1%, respectively. In addition, OLEDs using CC2TA as the emitting material show a relatively high external quantum efficiency of ext = 9.24% at 0.01 mA/cm2 with intense delayed fluorescence that exceeds the theoretical limitation of ext in conventional fluorescence based OLEDs.

8435-10, Session 2

Solution processed bi-layer small molecular weight solar cells with high open-circuit voltage

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We demonstrate solution processed neat bi-layer inverted solar cells using cationic cyanine dyes as the electron donor and a functionalized fullerene derivative as the electron acceptor. Cyanine dyes are interesting candidates for use in solar cells because of their very high absorption coefficients allowing a large number of photons to be absorbed in extremely thin layers. The cells exhibit high open circuit voltages of 1 volt, only 0.8 eV below the band gap of the cyanine dye. This is one of the smallest differences reported for organic solar cells and illustrates an almost optimal donor acceptor energy level alignment. Although higher efficiencies for small molecular weight materials can be obtained for BHJ architectures, these structures are at the same time difficult to control, especially if solution processed. They depend critically on the dimensions and extension of each of the two phases which is altered by the choice of solvent, processing conditions and annealing of the film. Therefore, there is still an interest to prepare planar donor-acceptor junctions as it allows for a better understanding of the device mechanisms. Additionally, it

serves as a platform to screen materials in a more straightforward way as the device performance can be considered a minimum achievable value.

8435-11, Session 2

Terpolymers based on benzotrithiophene for FET and OPV applications

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Benzotrithiophene has been recently introduced as new electron rich moiety for semi-conducting polymers.[1] The incorporation of this new donor unit into donor-acceptor type polymers has lead to high hole mobilities of ~0.3 cm2/Vs in organic field effect transistors and to organic photovoltaic devices with open-circuit voltages as high as 0.8 V. We present here our recent work on random benzotrithiophene terpolymers. [2, 3] A series of donor-acceptor terpolymers has been synthesized with the aim to increase the polymer absorption without affecting the HOMO energy levels, thus leading to higher short-circuit currents in photovoltaic devices with similar high VOC and ultimately better overall photocurrent efficiencies. We will discuss how the choice of the third monomer affects the physical properties of the polymers and a detailed study of the influence of monomer ratios on device performance will be presented.

[1] C. B. Nielsen; J. M. Fraser; B. C. Schroeder; J. Du; A. J. P. White; W. Zhang; I. McCulloch, Organic Letters 2011, 13, 2414-2417.

[2] B. C. Schroeder; C. B. Nielsen; Y. Kim; J. Smith; S. E. Watkins; K. Song; T. D. Anthopoulos; I. McCulloch, Chemistry of Materials 2011, 23, 4025-4031.

[3] C. B. Nielsen; B. C. Schroeder; R. S. Ashraf; Z. Huang; A. Hadipour; B. Rand; S. E. Watkins; J. Durrant; I. McCulloch, Journal of Materials Chemistry 2011, DOI: 10.1039/C1JM13393D.

8435-12, Session 2

Nonlinear optical properties of conjugated polymers

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Conjugated polymers have been intensively studied for the electrical, (linear) optical and electronic properties. This has led to several applications, such as oPV, oLED, ... Also the third-order nonlinear optical properties of conjugated polymers have been reported. Second-order nonlinear optical properties were not expected, since conjugated polymers lack the typically DπA motif (π-conjugated bridge, end-capped with an electron donating and - withdrawing group). Nevertheless, we recently experimentally discovered that conjugated polymers can show a remarkable high hyperpolarizability; depending on the solvent conditions, even record-high responses were observed.

An investigation of different conjugated polymers (poly(phenanthrene) s, poly(thiophene)s, poly(dithienopyrolle)s, poly(cyclopentadithiophene) s, ...) reveals that high hyperpolarizabilities are not restricted to one or a few conjugated polymers, but is a general feature. This opens the a possible new research domain for conjugated polymers. Moreover, the hyperpolarizability seems to strongly depend on the solvent conditions.

The questions remains why conjugated polymers show such high hyperpolarizability, certainly since the molecules do not obey the DπA structure paradigm. In this respect, this is useful to note that the highest hyperpolarizabilities are found in polymers with non-planar, irregular conformations (random coils and not, for instance, helices). This was shown in two ways. First, by measuring the hyperpolarizability of a poly(phenanthrene) in different solvent conditions (mixtures of chloroform and methanol) in which the conformation changes from random coils (neat chloroform) to helices (chloroform/methanol). Second, this could be concluded by comparing the hyperpolarizability of polymers with a different conformation.

These results are in perfect agreement with Kuzyk's postulation that the highest hyperpolarizabilities are found in conjugated molecules in which the effectiveness of the conjugation varies along the conjugated path. Indeed, in a planar conformation (rods), the conjugation, although possibly very strong, does not vary along the conjugated path; in helices, the angles between consecutive monomers are the same, again leading to no variation of the conjugation. In coiled polymers, however, the angles between the consecutive monomers vary, resulting in a 'varying potential energy landscape' and, consequently high hyperpolarizabilities.

8435-94, Session 2

Measuring efficiency losses in quantum dot polymer solar cells

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Molecular based photovoltaic devices have received much attention in recent years due to their potential low cost and their increase in light-to-energy conversion efficiency. Outstanding efficiencies (> 8%) have been achieved during the last years using different low band gap semiconductor polymers and fullerene derivative such as C60-PCBM or C70-PCBM. This breakthrough stems from the wide development of new polymers, however, very little attention has been focused on replacing the fullerene derivative molecules by other acceptor moieties. We believe that the use of nanocrystal quantum dots in bulk heterojunction solar cells could overcome the efficiencies that all organic photovoltaics have presented, due to the unique properties that this inorganic materials present as the possibility to fine tune their absorption spectrum and to carry out multiple exciton generation. Nevertheless, the efficiency of such devices has not reached similar values as the organic counterparts, yet. There is still a lack of fundamental understanding of the interfacial charge transfer processes that take place between the quantum dots and polymers. For that reason, we have studied the photo-induced charge recombination under working conditions that limit the device performance in polymer/quantum dot bulk heterojunction solar cells. We have employed spectroscopic techniques as L-TAS, CE and TPV to study the charge recombination dynamics in such a devices.

The recombination lifetimes for electrons and holes in the device showed a higher dependence with the light inteisty than other molecular solar cells such as bulk heterojunction organic solar cells. The implications of this unprecedent observation on the design of novel devices are discussed as well as the realtionship between the charge accumulation in these devices under operation conditions and the device open-circuit conditions.

8435-54, Poster Session

Tuning of superfine electron-nuclear interaction in ground structure in the series of multinuclear compounds and of characteristics of the full systems excited electronic states with the help of formation of effective photophysics and spectral-energy properties

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In the report a results of the measurements and of calculations the spectra of properties with application of the developed new complex of the computer of the programs realizing numerical methods and the semi-empirical quantum-chemical LCAO-MO SCF extend-CI PPP/S and INDO/S methods for the photophysical properties of some news and also some known of the organic compounds from experimental methods of spectroscopy are NMR 1H and 13C, a Infrared absorption (IRA-), a Raman of dispersion of light (RD-), a UV-electronic absorption (at 295K and 77), a fluorescence and phosphorescence (at 295K, 77 4), a Jet-spectroscopy (at 4K), at the lasers, a lamp, and electron-Ray of pumping, and others.

The spectral method allows on phenomena the super thin electron-nuclear interaction investigated in different environments between chemically of bonding of atoms in structure of the multinuclear compounds or in their various complexes to optimize their electronic structure and geometrical parameters in the ground states and the excited singlet and triplet electronic states in different environments for the optimization of parameters pumping in the given conditions, and from the OLEDs-, OTEDs, and other quantum of technology.

8435-55, Poster Session

Dye design for photoelectrochemical solar cells by changing the conjugation order: importance of computational errors

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Modification of conjugation order has emerged as a strategy of dye design for nano-structured solar cells which is alternative to the extension of p-conjugation. Effective use of this strategy requires the ability to predict changes in electronic properties with conjugation order. We show that when changing the conjugation order, computational errors are expected to be more important than in the case of an extension of the size of conjugation.

In dyes 2-Cyano-3-[5'-(4"-(N,N-dimethylamino) phenyl) thiophen-2'-yl] acrylic acid and Cyano-[5-(4-(N,Ndimethyl-amino) benzylidene)-5H-thiophen -2-ylidene]-acetic acid, the change of the position of the methine unit causes a difference in the absorption peak maximum of 61 nm in dioxane and 128 nm in acetonitrile, which is not predicted by TDDFT using GGA or hybrid functionals: even if absolute errors are within accepted ranges, they are different between the molecules, which leads to a qualitative failure of TDDFT to predict their relative energetics. In fact, TDDFT with the B3LYP functional predicts almost identical excitation energies for both dyes.

We identify a different between the dyes albeit small extent of charge transfer (CT) character as the origin of this failure. The difference in the spectrum is traced back to the quinoidization of the thiophene moiety by the electron-withdrawing anchor group, which is sensitive to long-range effects. For this reason, long range corrected functionals were found to perform better.

TDDFT errors in vacuum can be corrected based on the known trend of error with the degree of CT character suggested in J. Chem. Phys. 128 (2008) 044118. Alternatively, orbital energies can be used to monitor the relative energetics, as they are less sensitive to errors at long range. We also perform molecular dynamics simulations and show that nuclear motions affect similarly the spectra of both molecules likely lowering the observed excitation energy by a few percent.

The spectrum in acetonitrile is qualitatively reproduced by the same correction and deprotonation. We discuss the origin of the remaining errors in a polar solvent, in particular of different solvatochromism of the two molecules which is not reproduced by TDDFT calculations using the PCM solvent molecules.

8435-56, Poster Session

Behaviour of electron and hole currents in three layer heterostructure OLET

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Balance of electron and hole currents is essential for high performance ambipolar organic light emitting transistors (OLETs). The possibility for achieving high external quantum efficiency (EQE) from ambipolar OLETs in comparison with unipolar devices arises from the light generation inside the transistor channel aside the electrodes. This diminishes exciton-metal quenching and ensures that all the mobile charge is recombined (J. Zaumseil et al., Nature Mater., 5, 69, 2006). However, unbalance in the charge carrier currents leads to transfer of the light generating region closer to the drain electrodes that can potentially reduce EQE. This transfer can be compensated by using higher driving voltages (J. Zaumseil et al., J. Appl. Phys., 103, 064517, 2006). However, high driving voltage is an undesired solution. Therefore, balanced electron and hole currents are critical to obtain optimum ambipolar OLET performance.

In this study we examine balancing of electron and hole currents in three layer heterostructure OLETs by using the device configuration with the highest EQE to date that was demonstrated by R. Capelli et al. (R. Capelli et al., Nature Mater., 9, 496, 2010). The OLETs consist of separate layers of electron (α,ω-diperfluorohexyl-quaterthiophene) and hole (α,ω-dihexyl-quaterthiophene) transporters and a light emitting layer, Alq3:DCM, coevaporated from host and guest materials (tris(8-hydroxyquinolinato) aluminium):(4-(dicyanomethylene)-2-methyl-6-(p-dimethylaminostyryl)-4H-pyran) between the transporting layers. Devices were fabricated on glass substrate with patterned indium-tin-oxide film used as a gate electrode. Polymethyl(methacrylate) (PMMA) film was spin coated directly on the substrate to form the gate dielectric. All the active layers and interdigitated drain and source electrodes were evaporated on the substrate above the PMMA film. Transistors with channels of 100µm, 150 µm and 200 µm in length and 20 cm in width were fabricated. Effect of modifying layer thicknesses was examined. Further, changes in charge transport were compared between the studied OLETs and two layer organic thin-film transistors (OTFTs) of corresponding structure without the light emitting layer. Additionally, the effect of modifying doping ratio of the light emitting layer was investigated. Results show that compared to OTFTs, insertion of the light emitting layer significantly affects the current balancing process and deteriorates the morphology of the top transporting film. It was also found that the energy levels of light emitting layer effect the charge mobility of the top the transporting layer.

8435-58, Poster Session

Rectifying and negative differential resistance behavior in single tris(8-hydroxyquinoline) aluminum (Alq3) nanowire diode

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High quality Alq3 nanowires has been synthesized via a microemusion process. The morphology of the product was modified by the Tween 80. Powder X-ray diffraction patterns of Alq3 nanowires showed reflections at 2-theta f 6.4 degree which is indexed respectively to the [001] reflection of the meridional alpha phase. The Alq3 complete morphology transformation to nanowires leads to red shift (16 nm) of the photoluminescence peak. The red-shift emission of Alq3 nanowires may be attributed to the changes in the crystal structural with a complex. This is in good agreement with the XRD pattern.

A proposal growth mechanism of Alq3 nanowires was suggested. Firstly, a normal microemulsion of CHCl3 in H2O is formed by vigorous ultrasonication. When the emulsion is heated to the temperature 60 oC in a waterbath, the chloroform in some micelles slowly evaporated into the atmosphere due to its low boiling point, causing the concentration of Alq3 in the micelles to increase and eventually supersaturate which leads to nucleation. They grow into pyramid-shape structures due to the growth rate of [001] direction is faster than that of other direction which is mainly driven by crystal packing forces and p-p tacking interactions among adjacent Alq3 molecules.

A Schottky diode with single Alq3 nanowires across the Ag electrodes is fabricated. It could be seen that the current will flow through the probe, the Ag electrode, the Alq3 nanowire, the Ag electrode and the probe under a forward bias. For the Ag/Alq3 interface, it is generally by using Richardson-Schottky (RS) thermionic emission or Fowler-Nordherm tunneling model. The low forward turn-on voltage 0.5 V and high reverse breakdown voltage 15 V is obtained. A negative resistance behavior is observed when the forward bias exceeds 4 V and the peak to valley ratio in current is more than 6:1 at room temperature. The tunneling effect of tunnel diode and electrons/holes resonant tunneling cannot also occur in the device. Possible models for the origin of negative resistance may be the polarization model. The study can help us to open the development of organic/inorganic hybrid nanostructure device.

8435-59, Poster Session

Formation of pyramid-shape 8-hydroxyquinoline aluminum (Alq3) and its negative resistance behavior in a single pyramid-shape Alq3 diode

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High quality pyramid-shape Alq3 has been synthesized via a microemusion process. The morphology of the product was modified by the various concentrations of sodium dodecyl sulfate. Powder X-ray diffraction patterns of Alq3 powder showed reflections at 2-theta 6.4 degree which is indexed respectively to the [001] reflection of the meridional alpha phase. The Alq3 complete morphology transformation to pyramid-shape leads to red shift (35 nm) of the photoluminescence peak. The red-shift emission of pyramid-shape Alq3 may be attributed to the changes in the crystal structural with a complex. This is in good agreement with the XRD pattern.

A proposal growth mechanism of pyramid-shape Alq3 was suggested. Firstly, a normal microemulsion of CHCl3 in H2O is formed by vigorous ultrasonication. When the emulsion is heated to the temperature 60 oC in a waterbath, the chloroform in some micelles slowly evaporated into the atmosphere due to its low boiling point, causing the concentration of Alq3 in the micelles to increase and eventually supersaturate which leads to nucleation. Once the chloroform in a micelle is depleted, the nuclei move from the inner core of the micelle to the anionic headgroups of SDS (SO4-). They grow into pyramid-shape structures due to the growth rate of [001] direction is faster than that of other direction which is mainly driven by crystal packing forces and p-p stacking interactions among adjacent Alq3 molecules.

A Schottky diode with single pyramid-shape Alq3 across the Ag electrodes is fabricated. It could be seen that the current will flow through the probe, the Ag electrode, the Alq3 wire, the Ag electrode and the probe under a forward bias. For the Ag/Alq3 interface, it is generally by using Richardson-Schottky (RS) thermionic emission or Fowler-Nordherm tunneling model. The low forward turn-on voltage 0.5 V and high reverse breakdown voltage 15 V is obtained. A negative resistance behavior is observed when the forward bias exceeds 4 V and the peak to valley ratio in current is more than 6:1 at room temperature. The tunneling effect of tunnel diode and electrons/holes resonant tunneling cannot also occur in the device. Possible models for the origin of negative resistance may be the polarization model. The study can help us to open the development of organic/inorganic hybrid nanostructure device.

8435-60, Poster Session

Integrated light sources based on self-formed polymer waveguide doped with active medium

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Polymer waveguide devices have promise as integrated components in convenient optical systems such as the optical sensing microchip. Especially the self-formation method of the fiber type waveguide using the actively doped photopolymer, called as self-written active (SWA) waveguide technique, brings a simple fabrication scheme of integrated light sources. It has been demonstrated that the in-line optical amplifier and the Fabry-Perot type lasing cavity coupled with the other waveguides can be easily obtained by using the SWA waveguide technique. In this study, we have developed an incoherent light source with a wideband emission spectrum.

The wideband light source was realized by cascading the SWA waveguides with different emission bands. To realize such the configuration, a micro-patterned SU-8 film deposited on a silica substrate was used as the platform. The patterned SU-8 film had a thickness of 150 um and contained three microfluidic channels, in which the SWA waveguides with different organic dyes were fabricated, and the channel waveguide used as the output port. Into the microfluidic channels, the dye-doped photopolymer resins were injected. The three dyes used in this sample had the emission bands of red, green, and blue regions, which were Rhodamine 101, Coumarin 153, and Coumarin 120, respectively. After that, the laser light from a 375-nm LD was introduced using an optical fiber with a core diameter of 50 um. As a result of the self-confinement of the UV light, a dye-doped fiber-type waveguide could be self-formed. Since the formation of waveguide could be continuously induced in the three channels, the cascaded structure of three SWA waveguides was successfully fabricated. The length and diameter of the waveguide were ~1000 um and ~50 um, respectively. Under the irradiation by a conventional mercury lamp, each waveguide emitted, and the emission efficiently coupled to the SU-8 waveguide was output from the sample edge. Furthermore, the emission peaks of the three SWA waveguides were well overlapped, and thus the output emission with the white light spectrum was obtained. This device has promise as a convenient white light source to be integrated in various microchip-sensing systems.

8435-61, Poster Session

Investigation of covalent functionalized single-wall carbon nanotubes using Surface-Enhanced Raman Scattering

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Many of the applications of single-wall carbon nanotubes (SWCNTs) are limited by the challenges of manipulating and processing pure SWCNTs. One method that provides potential solutions to these issues is covalent functionalisation of SWCNTs which can provide the means to increase solubility, allow better dispersion, and facilitate the addition to surfaces or other molecules. The moiety covalently bonded to the nanotube sidewall can be controlled such that the electronic structure can permit a covalent attachment, allowing the nanotubes to assemble onto a substrate. SWCNTs possess optical and electronic properties that can be tailored by this covalent bonding to the nanotube thereby altering the conjugative network of the carbon structure.

Surface-Enhanced Raman Scattering (SERS) provides greater detection sensitivity than conventional Raman spectroscopy. The SERs enhancement mechanism originates in part from the large local electromagnetic fields caused by resonant surface plasmons that can be optically excited for metal particles of different shapes. We have prepared three Si covered silver film slides using defined evaporation parameters, which as substrates provide enhancement of the SWCNT electronic structure. Through oxidation processes, defect sites in the nanotube sidewall or at the open tube ends can be exploited for functionalisation at those sites. These oxygenated functional groups can be converted into other derivatives, including amides.

SWCNTs with covalently bonded amine groups were investigated using surface-enhanced Raman (SERs) spectroscopy assessing the impact of altering the electronic arrangement of the nanotube surface. The modeled peak shapes of tangential, disorder modes and radial breathing modes have been used to make comparison between SWCNTs conjugated with Fluoresceinamine and Azadipyrromethenehave. Excitation of nanotube samples at wavelengths in resonance with both metallic and semiconductor nanotubes was undertaken.

8435-63, Poster Session

Synthesis, optical and thermal properties of glassy trityl group containing luminiscent derivatives of 2-tert-butyl-6-methyl-4H-pyran-4-one

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One of most notable red luminiscent materials contain 2-tert-butyl-6-methyl-4H-pyran-4-ylidene fragment as backbone of the molecule. They are widely used in fields of photonics - such as materials for creation of molecular electronics elements, solar cells, solid state lasers and organic light emitting diodes (OLEDs). However, most of them are layed on OLED hole transport layer (HTL) by thermal evaporation or vacuum deposition. Some of them are used as dopants in polymers and spin-coated on HTL from solution together with polymer matrix.

In this work we present an original trityl group containing glassy luminiscent 6-styryl substituted derivatives of 2-(2-tert-butyl-4H-pyran-4-ylidene)malononitrile (DWK-1TB), 2-(2-tert-butyl-4H-pyran-4-ylidene)-2-cyanoacetate (KWK-1TB), 2-(2-tert-butyl-4H-pyran-4-ylidene)-1H-indene-1,3(2H)-dione (ZWK-1TB) and 5-(2-tert-butyl-4H-pyran-4-ylidene)pyrimidine-2,4,6(1H,3H,5H)-trione (JWK-1TB) and their simple preperation. Their optical properties have been investigated. The absorption maxima of synthesized glasses is from 425 nm to 515 nm and emission maxima is from to 470 nm to 625 nm in solution of dicholomethane. In their solid films absorption maxima is from 425 nm to 500 nm and emission maxima is in range from 570 nm to 710 nm.

Incorporation of bulky trityloxy ethyl groups combining with existing tert-butyl groups results in thin solid formation of synthesized glasses from volatile organic solvents (chloroform, dicholomethane) without them beeing doped in any polymer. This makes them perspective for potential applications in organic light-emitting diodes and organic lasers by simple luminiscent layer compsition with cheap spin-coating approach.

The thermal properties of glasses ZWK-1TB, DWK-1TB, KWK-1TB and JWK-1TB were examined by thermogravimetric analysis. All glasses show good thermal stability with thermal decomposition temperatures from 288o to 344oC. These thermal properties of synthesized glasses may make them also useful for potential applications in other optical materials such as materials for nonliner optics.

8435-64, Poster Session

Time-dependent charge carrier transport in organic light emitting diodes: modeling dark injection transients

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Designing and optimizing the complex multilayer stacks used in organic light emitting diodes (OLEDs) for large-area lighting or display applications requires a predictive model based on in-depth knowledge of the device physics. Such models should predictively describe the steady-state as well as the transient behavior, as probed under ac conditions.

For modeling charge carrier transport, efficient 1D models such as the Extended Gaussian Disorder Model (EGDM) [1] have been developed based on 3D supercomputer calculations, taking the energetically disordered nature of the materials into account. It was recently shown how, within the EGDM, the time-dependence of the mobility as resulting from charge-carrier relaxation should be described [2]. The model was found to appropriately explain large relaxation-induced effects on the frequency-dependent differential capacitance of devices based on a blue-emitting polymer.

In order to further validate this approach, an extensive study was carried out of dark injection transients measured for the same devices, for different layer thicknesses, voltage steps and temperatures. While the EGDM provides an accurate description of the steady-state current-voltage curves, there are significant deviations in the transient regime when the mobility is assumed to be time-independent. A first difference observed is in the saturation time of the current, which is predicted to be in the order of a millisecond while the experimental times are in the order of seconds, or longer. Secondly, the peak in the transient current density, often used as a convenient measure of the mobility, is observed at a much earlier time than predicted. We show that these deviations can indeed be explained as an effect of charge-carrier relaxation. For that purpose, we have carried out 1D modeling as well as 3D Monte Carlo simulations. We envisage that applying the relaxation model to double-carrier devices will provide a predictive model for transient electroluminescence.

[1]. W.F. Pasveer et al., Phys. Rev. Lett. 94, 206601 (2005).

[2]. W. Chr. Germs, J. J. M. van de Holst, S. L. M. van Mensfoort, P. A. Bobbert, R. Coehoorn, Phys. Rev. B, 84, 165210 (2011).

8435-65, Poster Session

Synthesis and properties of 2-dicyanomethylenethiazole merocyanines

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Dicyanomethylenethiazole chromophores have previously been reported in the literature, however little work has been undertaken employing the pyridylene donor. Our previous work investigated the effects of bulky substituents on the properties of chromophores containing tricyanofuran acceptor systems. This work investigated the formation of the desired base chromophore and attachment of bulky substituents. Variation of the adjacent group of the dicyanomethylenethiazole was also performed, with solubilising alkyl chains introduced to enhance the relatively poor solubility of the parent compound. The absorption spectra of all compounds were measured in a range of solvents to investigate the solvatochromism, which showed a wide change (spread over 200nm) in absorption maxima from polar to non-polar environments; however, upon going to solvents such as toluene and dioxane, a significant blue shift (140-170nm) is observed. Little change was observed in the absorption spectra upon introduction of bulky substituents. Fluorescence and excitation measurements were also performed, with multiple excited states observed in dichloromethane and significant fluorescence quenching observed in toluene and dioxane. At time of submission, Hyper Raleigh Scattering (HRS) measurements are intended to be performed in the near future.

8435-66, Poster Session

Luminescent properties of polymer nanocomposites activated with praseodymium-doped nanocrystals

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Recent years have observed the rapidly growing interest in polymer materials for application in compact, low cost light sources and amplifiers, specifically these operating in the visible spectral range. The polymer materials deployed in modern photonics, like e.g. poly(methyl methacrylate) (PMMA), are known to have the excellent mechanical properties and relatively good transmission over the visible spectral range, which in combination with the easiness of fabrication and low cost of mass production make them potentially attractive matrices for

active ions. Unfortunately, the direct doping by rare-earth ions results in significant quenching of the optical transitions, which is a result of interactions with highly energetic phonons, inherent for the polymer matrices, containing typically a huge number of extremely light hydrogen atoms. Doping of polymer material with optically active nanocrystals, isolating active centers from the influence of matrix's phonons may solve this problem, enabling development of a new class of photonic materials and devices. Such composite would combine the advantages of low cost and excellent mechanical properties of polymer matrices and the attractive luminescent properties of the embedded active nanocrystallites (which spectroscopic features are often better than bulk crystals).

In this work we report the recent results of our investigation on visible emission properties of the polymer nanocomposites doped with oxide and fluoride nanopowders activated with praseodymium ions. The set of LaAlO3 and YF3 nanopowders differing in active ions concentration, was carefully characterized with respect of their structural and luminescent properties. Moreover - the PMMA-based nanocomposites doped with these nanopowders have been manufactured and characterized. The measurements of excitation and emission spectra as well as fluorescence decays enabled comparison of emission properties of nano-composites and original nanopowders and in-depth discussion of the main excitation and de-excitation mechanisms, shaping the optical properties of developed materials. This, in turn enabled optimization of developed manufacturing technology. The results confirmed that nano-crystallites incorporated into polymer matrix tend to keep their original optical properties, both with respect of emission characteristics and fluorescence kinetics behavior, which means that active ions are effectively shielded from the interactions with the phonons of PMMA matrix, keeping the luminescent and lasing potential of the crystalline active medium combined with all advantages of the polymer host.

8435-67, Poster Session

Charge transport studies of polymeric photovoltaic thin films and their bulk-heterojunction blends with an electron blocking and trapping layer

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The injection and transport properties of two photovoltaic polymers, poly(3-hexylthiophene) (P3HT) and poly(2,7-carbazole) derivative (PCDTBT), and their polymer:fullerene bulk heterojunction (BHJ) are studied by space-charge-limited current (SCLC), dark-injection space-charge-limited current (DI-SCLC), and admittance spectroscopy(AS). For a nominally hole-only device, electrons leakage occurs. This results in a current larger than the theoretical SCLC and featureless DI-SCLC and AS signals. In order to prevent the electron leakage, a hole-transporting but electron blocking/trapping thin layer is added between active layer and Au. The layer composed of copper phthalocyanine (CuPc) doped into an amine-based small molecule. Using this interlayer, well-defined carrier transit times can be obtained for mobility extraction. Temperature dependent measurements show that PCDTBT has a significantly higher energetic disorder than P3HT for hole transport. With a suitable interlayer to suppress undesirable carrier injection and transport, these techniques should find broad applications in the transport characterization of narrow gap photovoltaic polymers and BHJ blends.

8435-68, Poster Session

Creation and investigation of photoexcitated organic semiconductor laser of the blue-green region of spectra

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Complex approach (theoretical and experimental methods) for investigation of the spectral-luminescent and lasing properties of the organic semiconductor lasers ate used. Theoretical methods consist of semiempirical INDO method with unique novel technique for estimation of radiative and nonradiative rates and mathematical modeling of photoexcited lasers. This approach allows to select more perspective organic structures from studied molecules for OSL creation. Perspective structures for creation of organic semiconductor lasers are chosen. Experimentally the properties of created thin-film structures under the pumping of 3rd harmonic of Nd:YAG laser are investigated. The ways of improvements of OSL characteristics by changing the structure of organic thin-films are selected.

8435-69, Poster Session

N-vinylcarbazole based materials for photonics

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The elaboration of photosensitive polymeric systems for photonics remains topical on contemporary stage and is of a particular theoretical and practical interest [1]. In this work we present the synthesis and investigations of N-vinylcarbazole copolymers (N-VC) with 4-decylstyrene (4-DS). In the obtained material the N-vinylcarbazole units are responsible for photosensitive properties while the co-polymerized 4-decylstyrene units are responsible for the plasticisation effect.

The synthesis of binary copolymers with a variable N-vinylcarbazole content (from 60 to 80 mole%) was realized using free radical polymerization method in the presence of 1 or 2 mole % of initiator (azobisisobutyronitrile), in toluene or tetrahydrofuran, in inert gas atmosphere, in sealed ampoules at 80°C. All copolymers were purified by double precipitation in methanol. The structure of synthesized copolymers was investigated using IR, UV-VIS and 1H NMR spectroscopies and elemental analysis.

The N-VC:4-DS copolymers' thin films were sensitized with 2,4,7-trinitro-9H-fluoren-9-one and other ingredients. The investigation of copolymer films photo-electro conductivity showed performing results (S>10-5J/cm2), especially for the copolymer containing 20 mole% of 4-DS as plasticiser. As it was previously showed [2], phthalocyanines are good agents for the increase of carbazole-containing materials photosensitivity. The introduction of 5-10 % of Zn, Co or Ni tetraoctyloxyphthalocyanine shifts the photosensitivity maximum from 400-600 nm to 800 nm.

A double-layered optical information recording media was developed from N-VC:4-DS copolymers. Using the green (λ=532 nm) and red (λ=633 nm) lasers irradiation diffraction gratings with the diffractional eficiency of 10% and resolution R = 1000 - 2000 mm-1 were recorded.

8435-70, Poster Session

A comparison of printing and coating techniques for the production of large-area polymer light-emitting diodes

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One of the important aspects of organic electronics is its solution processability which allows the utilization of high throughput and low cost roll-to-roll printing and coating techniques for the preparation of large-area optoelectronic applications such as Organic Light Emitting Diodes (OLEDs)[1]. In the past decade screen printing, inkjet printing and spray coating where introduced as promising candidates, however spin coating remains the conventional method for the production of laboratory-scale devices[2].

In this study a systematic comparison is drawn between spin coating on one side and screen printing, inkjet printing and spray coating on the other side. The Hole Injection Layer (HIL), i.e. PEDOT:PSS, and the organic light-emitting layer will be deposited using these various deposition techniques on patterned Indium Tin Oxide (ITO) glass substrates, while the top contact will be, for all devices, produced by the thermal evaporation of a thin calcium-Aluminum film. The morphology and layer thickness of the conjugated polymer films are studied by means of contact angle and electron microscopy tools. The resulting light-emitting diodes are compared by their electro-optical behaviour, i.e. I-V curves, luminance efficiencies, power efficiencies and external quantum efficiencies. Thus giving a comprehensive and complete overview of the current state-of-the-art printing and coating techniques yielding high efficient and uniform polymer light-emitting diodes.

[1] S. Hameed, et al, Reviews On Advanced Materials Science, 26, p30-42, 2010

[2] F.C. Krebs, et al, Solar Energy Materials & Solar Cells, 93, p394-412, 2009

8435-71, Poster Session

Spectral, luminescent, and electroluminescent properties of linear divinyldiphenylthiophenesulfone derivatives

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Spectroscopic and electroluminescence properties of five new linear divinyldiphenylthiophenesulfone derivatives are presented. It was found that the studied compounds have rather high photoluminescence efficiency in solution as well as amorphous and PVK blend films in blue and blue-green spectral range. Bright blue electroluminescence of these compounds has been obtained in single layered structure ITO/PEDOT/PVK:OC/Al small molecules and polymer chains strongly effect on both luminescence efficiency and conductivity that have to be taken into account while developing high perfomance electroluminescent structures. Spectral and luminescent properties of new molecules were studied for thin films of two kinds: pure thermo vacuum deposited amorphous organic materials and these materials embedded into polymer matrix. The studied structures have rather high photoluminescence efficiency in amorphous and PVK blend films in blue and blue-green spectral range. Bright blue electroluminescence of these compounds has been obtained in single layered structure ITO/PEDOT/PVK:OC/Al with threshold voltage of 6-7 V.

8435-72, Poster Session

Extraction of circuital parameters of organic solar cells using the exact solution based on Lambert W-function

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The electrical behavior of an organic solar cell has been analyzed using a simple circuital model consisting in an ideal diode together with a series and parallel resistances (Rs and Rp). The solution of the current as function of the applied voltage leads to a transcendental equation that can be solved with no approximations using the numerical Lambert W functions. Theoretical expression has been fitted to experimental J-V curves, obtaining fairly accurate values for the electrical parameters. This model has been validated comparing the extracted parameters for dark and illuminated J-V curves. Results show good agreement in Rs, Rp and ideality factor (η). The inverse saturation current, J0, shows a severe deviation attributed to the photocurrent (Jph) voltage dependence.

Results obtained in this work are compared to those ones extracted using approximated methods based on algebraic manipulation neglecting some terms in the J(V) expression. These approximated methods are often employed by other authors [1]. We conclude that approximated methods lead to reasonable good values for Rs and η. However Rp and J0 differ in several orders of magnitude when using exact and approximated methods. In this work we have used the solutions of the approximated method as initial seeds to numerically fit the Lambert based function to the experimental data.

To validate the model, a bunch of organic solar cells with structure ITO/PEDOT:PSS/ poly(3-hexylthiophene) (P3HT): 1-(3-methoxycarbonyl)-propyl-1-1-phenyl-(6,6)C61 (PCBM)/Al has been fabricated in inert atmosphere. For the sake of comparison, different active layers were deposited varying the P3HT:PCBM ratio (1:0.64, 1:1, 1:1.55) and the active layer thickness (ranging from 100 to 280 nm). Devices are encapsulated prior its characterization outside the glove-box.

Values extracted for Rs range between 140 and 450 Ω, values for Rp range between 0.5 and 1.5 GΩ. Ideality factor ranges between 5 and 20 and J0 ranges between 10 and 330 μA/cm2.

[1] Yang Shen, Kejia Li, Nabanita Majumdar, Joe C. Campbell, Mool C. Gupta, "Bulk and contact resistance in P3HT:PCBM heterojunction solar cells", Solar Energy Materials and Solar Cells 95, 1-4(2011).

8435-73, Poster Session

Strongly emitting Pt(CN)2(CNR)2 stacks: luminescence color tuning by variation of the isocyanide ligands

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Square-planar Pt(II) complexes of the general formula $Pt(CN)_2(CNR)_2$ tend to form linear stacks stabilized by intermolecular Pt-Pt interactions. The photophysical properties of these stacks are distinctly different from those of isolated $Pt(CN)_2(CNR)_2$ complexes. In particular, the stacks are strongly luminescent. The emission energies of the crystalline $Pt(CN)_2(CNR)_2$ materials correlate with the Pt-Pt distances *D*, determined by X-ray investigations, according to a D^{-3} dependence, similarly as found for tetracyanoplatinates.[1,2] The $Pt(CN)_2(CNR)_2$ compounds exhibit very high emission quantum yields and short decay times. For example, for neat $Pt(CN)_2(CNC(CH_3)_3)_2$ at ambient temperature one finds the emission maximum at 542 nm, the quantum yield of 80 %, and the emission decay time of 1.2 μs.

1. G. Gliemann, H. Yersin, Struct. Bond., 1985, 62, 87-153.

2. H. Yersin, G. Gliemann, U. Rössler, Solid State Commun., 1977, 21, 915-918.

8435-74, Poster Session

Manufacturing polymer light emitting diode with high luminescence efficiency by solution process

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We fabricated PLED with Ir(mppy)3 doped PVK emission ink. Ir(mppy)3 which have good solubility can improve surface morphology than those of Ir(ppy)3. E-O characteristics of these devices by layer thickness of EMLs for printing process have been investigated. The less the thickness of EMLs, the higher luminescence was achieved. Particularly, A30 shown twice as much as luminescence of A50 and A80 with current density of 10mA/cm2. We also confirmed that A30 achieved lower operating voltage than those of A50 and A80 at current density of 10mA/cm2. E-O properties can easily affect by annealing conditions of EMLs. Thus, we examined luminescence efficiency according to annealing condition of EMLs. Luminescence efficiency of B30 and C30 devices were measured higher than those of A30. Nevertheless, the different was not significant. We also confirmed that EL spectra of polymer-OLEDs were influenced by concentration of PVK and thickness of emission layer. But it was not

affected by doping concentration of EML. It conjectured that thickness of emission layer which was affected viscosity of emission ink (including thickness of emission layers according to spin coating condition) decide position of coupled electron and hole. To sum up the experimental results, we optimized device structure of polymer-OLEDs with high color purity for applications in flexible display.

8435-75, Poster Session

Cu(I) dimers with high emission quantum yields for singlet harvesting in OLEDs

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In this study, a series of three Cu(I) dimers is presented that exhibit emission quantum yields of up to 85 % at short emission decay times of 3 µs. Further, the emission wavelength can be tuned from the deep blue to the green range of the visible spectrum by modifying the chemical structure. Detailed photophysical characterizations reveal that the emission at ambient temperature mainly originates from the singlet state S_1 which is thermally populated from the energetically close-lying triplet state T_1. The energy difference $\Delta E(S_1\text{-}T_1)$ between these states are as low as 460 cm^{-1}. It is proposed to utilize this effect of thermally activated delayed fluorescence to collect both singlet and triplet excitons [1] for light generation in OLEDs (singlet harvesting effect [2]).

[1] H. Yersin (ed.), Highly Efficient OLEDs with Phosphorescent Materials, Wiley-VCH, Weinheim 2008.

[2] H. Yersin, A. F. Rausch, R. Czerwieniec, T. Hofbeck, T. Fischer, Coord. Chem. Rev. 2011, 255, 2622 - 2652.52.

8435-76, Poster Session

Relation of energy levels in thin films of polar photoconductive molecules

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Among organic semiconductors, group of indandione molecules with their thermal and chemical stability and photoelectrical properties are good candidates for using them in novel electronic devices, for example-organic solar cells.

The fundamental part of designing such solar cells is knowledge of energetic parameters of materials. An ionization potential and energy gap directly affect such important electronic processes as charge carrier generation and transport. In order to characterize energy structure several parameters are determined such as an optical energy gap EGOpt, a threshold of quantum efficiency of photoconductivity Eth, difference between oxidation and reduction potential (Uredox).

Photoconductivity quantum efficiency and its spectral dependence of dimetilaminobenzylidene-1,3-indandione (DMABI) and several its derivatives was obtained. Value of the threshold energy Eth from spectral dependence of quantum efficiency of photoconductivity is obtained. From optical absorption spectra the values of optical gap (EGOpt) were determined. The values of oxidation and reduction potentials were measured by voltamperometry.

We have determined linear relation between values of optical gap EGOpt and threshold energy Eth for DMABI and nine derivatives depending on redox potential Uredox. Also relation of the difference between optical gap EGOpt and quantum efficiency of photoconductivity Eth depending on molecule dipole moment is studied. Such knowledge could help to judge about DMABI derivative and its energetical structure faster after determination just one or two energetical values without spending time on long experiments.

8435-77, Poster Session

AC-driven light emission from in situ grown organic nanofibers

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Recently we have shown that in-situ growth of nanofibers using a gold film as substrate is a promising alternative to direct integration of the nanofibers with metal electrodes [1]. During this in-situ growing process, the crystalline organic nanofibers are directly formed onto device substrates by self-assembly of organic molecules via physical vapour deposition. The in-situ grown crystalline nano-aggregates are promising candidates for the next generation nano-scale waveguides and light sources, e.g. organic light-emitting transistors (OLETs), due to their unique properties such as emitting intense light under UV excitation and tuning the properties by molecule modification. It has been demonstrated that organic thin films can emit light driven by AC gate voltage [2]. We have also shown that deep blue electroluminescence from para-hexaphenylene thin films can be achieved by operating OLETs with an alternative gate voltage [3].

In this study, we obtain AC-driven electroluminescence from OLETs based on in-situ grown para-hexaphenylene nanofibers, which are grown by physical vapour deposition directly on the device substrates under high vacuum conditions. The device substrate consists of highly doped silicon as back gate and silicon dioxide as dielectric. The interdigitated drain and source electrodes are fabricated by electron beam lithography, gold deposition and lift-off. The electroluminescence intensity of these OLETs exhibit dependence on the frequency and amplitude of the AC gate voltage, indicating electron injection assisted by the generation of positive space-charge field formed by hole injection in the vicinity of the gold electrodes [3]. On-going studies focus on in-situ growth of multilayer nanofibers by sequential deposition of two different molecules.

[1] R.M.D. Hansen, M. Madsen, J. Kjelstrup-Hansen, and H.-G. Rubahn, Nanoscale Res. Lett. 6:11 (2011).

[2] T. Yamao, Y. Shimizu, K. Terasaki, and S. Hotta, Adv. Mater. 20 (2008) 4109-4112.

[3] X. Liu, J. Kjelstrup-Hansen, H. Boudinov, and H.-G. Rubahn, Org. Electron. 12 (2011) 1724-1730.

8435-79, Poster Session

Influence of sputtered contacts on the performance of organic solar cells

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The performance and stability of polymer based organic solar cells are strongly dependent on the type of metal contact which is applied. In the majority of cases the negative electrode of organic solar cells is a metal deposited by thermal evaporation. However, evaporation is not the method of choice for large areas. Magnetron sputtering is a more easily upscalable deposition method but up to now it has been avoided in most studies, due to expected plasma damage of the underlying polymer layer. In this contribution bulk heterojunction organic solar cells with sputtered metal contacts are studied. The photoactive thin film consisting of mixed poly(3-hexylthiophene) (P3HT) and the fullerene derivative [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) was deposited by spin coating from a chlorobenzene solution. The substrates used were patterned ITO covered glass coated with PEDOT:PSS. The thickness of the active layer was varied by changing the concentration of the solution used. After the deposition procedure the P3HT:PCBM films were kept in the solvent vapours for 10 minutes in order to stabilize the coatings. Metal electrodes of aluminium or silver were sputtered through a shadow mask. In the sputtering chamber the samples were subjected to thermal annealing in Ar with different parameters (temperature and duration) before and after the sputtering. The active area was encapsulated using a thin glass plate and UV curable epoxy resin. The solar cells were characterized by measuring their current-voltage curves in the dark and under illumination. Attempts were made to determine the effective series and shunt resistances of the obtained solar cells by means of impedance spectra measurements. The degradation of the devices was followed by determining their parameters at regular intervals during prolonged illumination. The results of the investigation indicate that sputtered contacts perform very well after suitable annealing. Degradation however is still considerable in an interval of several days and comparable to that of cells with evaporated metal contacts under similar conditions.

8435-80, Poster Session

Perylene bisimide derivatives as innovative sensitizers for photorefractive composites

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Photorefractive materials are one important field in the frame of organic semiconductors. Large research efforts in this field have been made to replace the commonly used inorganic crystals which provide many disadvantages like high fabrication costs and typically small size. The concept of photorefractive polymer composites turned out to be promising because of their excellent processability and adaptability. In these composites, each component performs a single function of the photorefractive effect. Dye molecules, so-called sensitizers, are responsible for charge generation. After charge separation by an applied external electric field, mobile holes are transported by charge transport agents, i.e., polymers, while electrons remain immobile. Electro-optic units, e.g., liquid crystals, react with a refractive index change on the redistributed charges.

Photorefractive composites are ideal candidates for fabrication of biomedical tomographs [1], novelty filters [2], data storage systems [2], and holographic displays [3]. To meet the requirements of these applications, one limitation has to be overcome: low photorefractive speed. In our contribution, we present an optimization of the photoconductivity and hence photorefractive speed by employing more efficient charge generators. In the well-known composite PCBM:PVK:5CB, we replace the fullerene derivative PCBM by perylene bisimide derivatives as high-performance sensitizers [4], which provide outstanding properties like strong light absorption in the visible range, excellent photostability, and high electron affinity. The composites are characterized by absorption spectroscopy, photoconductivity measurements and the two-beam coupling experiment. Improved photorefractive speed and enhanced two-beam coupling gain are observed, even when the sensitizer content is reduced [5].

Acknowledgement

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References

[1] M. Salvador, et al., Opt. Express 17, 11834 (2009).

[2] O. Ostroverkhova, W. E. Moerner, Chem. Rev. 104, 3267 (2004).

[3] P.-A. Blanche, et al., Nature 468, 80 (2010).

[4] H. Qian, et al., J. Am. Chem. Soc. 129, 10664 (2007).

[5] K. Ditte, et al., submitted to Advanced Materials (2011).

8435-81, Poster Session

Light-emitting thin films of glassy forming organic compounds containing 2-tert-butyl-6-methyl-4H-pyran-4-one

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Organic compounds become more useful in light emitting systems like organic light emitting devices (OLED) and lasers. Most of them are made from small molecules by thermal evaporation in vacuum or polymers by wet casting. But there are third possible way - make thin films from small molecules by wet casting. In such approach we can combine benefits from previously mentioned methods. Synthesis of small molecules is more repeatable than polymers and wet casting could use less material for film preparation than thermal evaporation in vacuum.

In this work we will show electrical, electroluminescence properties and amplified spontaneous emission (ASE) in spin-coated glassy forming organic compounds containing 2-tert-butyl-6-methyl-4H-pyran-4-one group. Thin films were prepared from dichloromethane solutions. Light emission was observed in yellow and red spectral region. Optical and electroluminescence measurements were carried out in ambient atmosphere at room temperature.

Nd:YAG laser second (532 nm) and third (355 nm) harmonic with repetition rate 10Hz and pulse duration 150 ps was used as light source for ASE measurements. The irradiation area on surface of the sample was stripe form with dimension 5x1 mm2. Light emission was measured at the edge of the sample. The threshold value of ASE was obtained from dependence of luminescence spectra on irradiation intensity. For the best compound the threshold value of ASE was about 100 J/cm2. Electrical properties and local trapping states of thin organic films with ITO and Al electrodes in the regime of space charge limited currents were studied. In turn, the system ITO/PEDOT:PSS/organic compound/BaF/Al was used for the electroluminescence measurements.

Electrical, electroluminescent properties and amplified spontaneous emission of 4 organic compounds containing 2-tert-butyl-6-methyl-4H-pyran-4-one group will be discussed.

8435-82, Poster Session

Temperature influence on photoisomerisation kinetics in thin polymer films doped with carboxyl group azobenzene derivative

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One of the promising fields of azobenzene molecules could be holographic recording of refractive or surface relief grating. Photoisomerization mechanics of azobenzene molecules give main impact in this process. At the same time photoorientation process may start. Temperature could play important role in understanding of the photoinduced processes in host - guest films.

Our investigation is dedicated to thermal impact of photoisomerisation kinetics of carboxyl group containing azobenzene molecules 6-[4-(4-dicyclohexylsulfamoyl-phenylazo)-phenoxy]-hexanoic acid in thin films. This compound shows spectrally separated isomers in absorption spectra in solutions and thin films. Host - guest system was prepared from chloroform solution with polymethilmetacrylate as host and azobenzene carboxylic acid as guest by spin coating method. In experiment different concentrations of guest molecules in polymer were chosen. Film thickness was up to 3 m in order to obtain equal absorption of the films in trans band. As a light source light emitting diode with 365 nm and 450 nm wavelength was used, which is close to absorption maximum of trans (360 nm) and cis (450 nm) isomers, respectively. Kinetic of transmission of polymer film at 365 nm was recorded during the irradiation of the sample with 365 nm and 450 nm wavelengths at different temperatures. The dependence of response time and changes of transmission on temperature of host - guest films with different concentration of azobenzene carboxylic acid will be analyzed in the work.

8435-83, Poster Session

NIL fabrication of a polymer based photonic sensor device in P3SENS project

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We present the most recent results of EU funded project P3SENS (FP7-ICT-2009.3.8) aiming at the development of a low-cost and medium sensitivity polymer based photonic biosensor for Point of Care applications in proteomics.

The fabrication of a polymer based photonic chip by using NanoImprint Lithography (NIL) is described. This technique offers the potential for very large production at reduced cost (once the NIL technique has been optimised to the specific materials, it could be transferred to a kind of roll-to-roll production for manufacturing a very large number of photonic devices at reduced cost).

The first step of the fabrication consist in spin-coating a thin polyimide film (below 1 µm thick, refractive index 1.64) on top of a TEOS oxyde (refractive index 1.45) on Si wafer. In order to increase the refractive index contrast of the polymer stack, polyimide was doped with TiO_2 nanoparticles. Cross-sections of the nanoimprinted waveguides prove the good quality of both doped materials and waveguides (the nanoparticles are uniformly distributed into the polymer matrix and waveguide trenches are also clearly visible). However, doping could lead to degraded waveguiding properties due to the increase of the extinction coefficient above 10-4.

Three level NIL stamps, including waveguides, shallow I/O couplers and Bragg mirror Fabry-Perot resonators are produced by e-beam lithography of a silicon substrate, and then used for NIL patterning the top layer (polyimide) of the optical stack. Both standard NIL process (polymer stack heated at 110°C) and hot-stamping process (stamp heated up to 375 °C) have been used for patterning the polyimide layer. Patterning on low index substrate proves however difficult as the softer fluorinated polymer substrate yields under too high applied pressure.

Resonator Q-factor up to 4500 and throughput attenuation up to 10 dB have been demonstrated on the Polyimide/TEOS/Si stack at 1310 nm wavelength depending on the resonator to bus waveguide coupling distance.

More work is now undergoing for patterning polyimide on the softer fluorinated substrate as a route towards a full polymer stack and higher surface sensitivities. The work includes the optimization of the NIL stamp geometry in order to ease the polyimide flow and be able to work at reduced pressure in order to avoid substrate yield.

8435-84, Poster Session

Synthesis and characterization of RE3+:Al2O3 nanopowders for application in the polymer based composite light sources

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The continuous need for low-cost, compact light sources operating at wavelengths extending from ultraviolet to infra-red, stimulates the investigations on novel type of optically active materials for application in modern photonics. This effort has already resulted in the significant progress in the technology of semiconductor light sources, including both LEDs and laser diodes. It should be noted, however, that there is still a plenty of room for development of novel, efficient light sources, offering possibility of low-cost mass production. During the last decade optically active nanopowders have attracted specific researcher's interest, resulting mainly from the observation, that a reduction of particle size is often accompanied by significant improvement of luminescent properties of such nano-material. That unique optical properties of nanopowders can be effectively used in novel generation of active media, including phosphors and coherent as well as non-coherent light sources. In particular, it seems that polymer based composite structures doped with optically active nanopowders may combine the advantages of excellent mechanical properties of low-cost polymer host and excellent luminescent properties of rare-earth ions in crystalline matrix, thus providing an interesting alternative for classical light emitting materials.

Among other investigated materials, aluminum oxide (Al_2O_3) seems to be still a promising host for active ions due to its optical transparency over broad spectral range, excellent mechanical properties and good chemical stability. When doped with rare-earth ions, it should be a good probe for studying optical behavior of nanometer-sized, optically active powders and composite polymer-based materials doped with these nanopowders. In this work we report first results of our investigations on synthesis as well as structural and luminescent properties of RE^{3+}:Al_2O_3 nanopowders prepared by a novel method, in which organic compounds are used as a solvent and lanthanide organic derivatives serve as a rare-earth source. We report and discuss also the properties of PMMA-based composites activated by these nanopowders.

The set of the Al_2O_3 nanopowder samples doped with RE^{3+} ions (where RE=Yb, Pr or Er) differing in activator concentrations and gradation levels has been carefully examined with respect of their structural and optical properties. The first PMMA-based composites doped with Al_2O_3 nanopowders have been manufactured and characterized in the context of their mechanical, structural and luminescent properties. The investigations have confirmed applicability of developed synthesis method to manufacturing of optically active nanopowders of high structural quality, low level of agglomeration and good homogeneity, consisting of nanoparticles with average size in the range of several tens of nanometers as well as possibility of developing the active composite material, based on PMMA polymer host.

8435-85, Poster Session

Solvent effects on morphology and spectral emission of PVK and PVK-Ir(ppy)3 based OLEDs

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Despite OLED displays have reached the commercialisation level, there is still a need for materials development with regard to efficiency, colour purity and stability. In the last few years there is a fast increasing interest in developing efficient white light emitting OLED (1).

Both small molecules and polymers are currently the preferred candidates. Polymers are generally of lower purity than small molecules but can access full colour and larger display sizes at much lower costs using solution-based deposition techniques.

Previous works have reported high brightness devices using the blue emitting polymer, poly(n vinylcarbazole) (PVK), as a host material to which an organometallic complex, like Iridium complexes, is added as a dopant (2). The heavy metal atom at the centre of the complexes presents strong spin-orbit coupling, facilitating intersystem crossing between singlet and triplet states. By using these phosphorescent materials, both singlet and triplet excitons will be able to decay radiatively, hence improving the internal quantum efficiency compared to a standard OLED where only the singlet states contribute to emission of light.

In this work we have compared the effect of using solvents with different boiling temperatures on the organization of the polymer on the substrate. The modified molecular rearrangement also effects the emission proprieties of the PVK material and the consequent energy transfer to the doping molecules. The different morphology has been probed by AFM measurements, the static and dynamic emission has been compared.

Finally different devices have been prepared to test the change in electroluminescence spectral shape and in electrical characteristics. Moreover the final efficiencies of the devices have been evaluated.

This work will also be compared with previous works where the effetct of different solvents has been studied in terms of emission bands and delayed electroluminiscence (3).

(1) Williams, E. L., Haavisto, K., Li, J. & Jabbour, G. E. Adv. Mater. 19, 197 (2007).

(2) N.J. Lundin, A.G. Blackman., K. C. Gordon, David L. Officer, Angew. Chem. Int. Ed. 45, 2582 (2006)

(3)L.Qian, D.Bera,P. H. Holloway, Appl. Phys. Lett. 90, 103511 (2007)

8435-86, Poster Session

Enhancing the color gamut of white displays using novel deep-blue organic fluorescent dyes to form color-changed thin films with improved efficiency

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This paper we use novel fluorescence based deep-blue-emitting molecules, namely BPVPDA .Organic fluorescence color thin film using BPVPDA exhibit deep blue fluorine with CIE coordinates of (0.13,0.16) and all organic dye are decomposition temperature (Td) that ER53(R) at 335.78, C545T (G) at 328.69, TPBe (B) at 357.08, BPVPDA at 260.88. High thermal stability of organic dyes.All heating was carried out at the rate of 10 min -1 under nitrogen atmosphere and all organic fluorescence dye exhibit high thermal stability temperature that comparing with the TFT-LCD and OLED higher temperature process. That developed an original "Organic RGB color thin films technology, which enables us to optimize the distinctive features of an organic light emitting diode (OLED) and (TFT) LCD display, color filter structure to keep the same high resolution, and obtain a higher brightness in comparison with conventional organic RGB color thin film. An image-processing engine is also designed to achieve sharp text image for thin-film-transistor (TFT) LCD with the organic color thin films. In Organic color thin films structure, we use organic dye dopent in limpid photo resist. With this technology, the following characteristics can be obtained: (1) high color reproduction of gamut ratio (2) high luminous efficiency with a organic color fluorescence thin film. This performance is among the best results ever reported for Color-filter using on TFT-LCD and OLED.

8435-87, Poster Session

The role of molecular packing on the UV-visible optical properties of [Re2Cl2(CO)64,5-(Me3Si)2pyridazine]

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We report here on two stable polymorphs of the dinuclear complex [Re2(μ-Cl)2(CO)6(μ-4,5-(Me3Si)2pyridazine)]. The compound belongs to the recently reported class of dinuclear luminescent Re(I) complexes of general formula [Re2(μ-Cl)2(CO)6(μ-1,2-diazine)], which exhibit emission in solution from triplet metal-to-ligand charge transfer (3MLCT) excited states.

Either monocrystals, polycrystalline films, or amorphous samples were grown by different growth techniques. In the solid state, the complex exhibits a unique combination of unusual properties: (i) concomitant formation of two highly luminescent polymorphs, and single crystal-to-single-crystal conversion of one form into the other, (ii) remarkable differences in the absorption properties of the two polymorphs due to different redistribution of oscillator strength among the different excitons, and (iii) remarkable differences among the emission properties. In particular, a higher emission quantum yield was found in the solid state than in solution (measured to be 0.52 and 0.56, respectively, almost one order of magnitude higher than that of the molecule in solution).

Interest in luminescent materials able to efficiently emit in the solid state is continuously growing, because in most applications the dyes are used as solid films. Although rigid environments are expected to freeze roto-vibrational relaxation pathways, luminescence efficiency often decreases in the solid state with respect to liquid solution due to concentration quenching, affecting both organic and organometallic emitters. However, an increasing number of molecular-based emitters exhibit enhanced solid state emission. Apart from the importance of bulky substituents in reducing concentration quenching effects, other intra- or inter-molecular phenomena have been invoked as well, such as conformational changes, π-π stacking, hydrogen bonds, or J-aggregates, which cause rearrangements of the energy levels and population. In these two polymorphs the enhancement of the emission with respect to the solution is most likely due to the restricted rotation of the Me3Si groups in the crystals, providing an interesting example of aggregation-induced emission effect (AIE).

Notably, crystalline phases proved to be more efficient emitters than their amorphous counterparts, showing the influence of molecular packing on the solid-state emission. The presence of the bulky trimethylsylil substituents on the chromophoric ligand, which prevent a close intermolecular approach should be taken into account, but is this a necessary condition for observing enhanced emission upon aggregation? To provide more insight into the phenomenon, we present a combined computational and experimental study in the framework of crystal optics in the aim to explore the role of molecular packing on the UV-visible absorption and emission properties of the two known polymorphs of [Re2(μ-Cl)2(CO)6(μ-4,5-(Me3Si)2pyridazine)].

8435-88, Poster Session

Looking at bulk-heterojunction organic photovoltaics from two viewpoints: morphology and charge transfer

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Organic photovoltaics (OPVs) have received much attention recently, but despite this they still show efficiencies below those of conventional silicon photovoltaics [1]. To date the highest OPV efficiencies have been found for so-called bulk-heterojunction (BHJ) solar cells, where the active layer is a bi-continuous composite of donor and acceptor phases. A conjugated, light-excitable polymer is most often used as an electron donor, and fullerene derivatives are the most widespread type of electron acceptor due to their high electron affinity and ability to transport charge. Such systems can essentially be looked upon as a polymeric blend. Like in polymer blends, the morphology formed will strongly influence the material characteristics, and post-production annealing has been shown to increase device efficiencies [2-3].

In this study, the active layer of BHJ solar cells is analysed using techniques that have in the past provided valuable information for polymer blend systems, such as fast-scanning calorimetry techniques and atomic force microscopy (AFM). Fast-scanning calorimetry is used to investigate the transitions that play a role in stability and morphology development of BHJ devices. In particular, fast scanning differential chip calorimetry (FSDCC) [4] shows great potential for these systems due to the very high scanning rates and the ability to study thin layer samples, like in actual BHJ devices. AFM techniques are used to visualise the formed morphologies, and their charge transfer properties are analysed using conductive AFM (C-AFM).

In addition to the experimental work, theoretical studies have been performed in order to gain a better insight into the charge generation and dissociation processes at the donor/acceptor interface. This system is modelled using ab initio Density Functional Theory (DFT) calculations under periodic boundary conditions (PBC). A possible bridge state, allowing charge transfer, was found for the excited triplet state of the

combined donor/acceptor system. A similar bridge-state was described previously in literature [5]. The excited singlet state requires analysis with time-dependent DFT techniques [6].

1. Tompson B.C., Fréchet J.M.J., Angew. Chem. Int. Ed., 47, 58-77 (2008).

2. Erb T., Zhokhavets U., Gobsch G., Raleva S., Stuhn B., Schilinsky P., Waldauf C., Brabec C.J., Adv. Funct. Mat., 15, 1193-1196 (2005).

3. Hoppe H., Sariciftci N.S., J. Mater. Chem., 16, 45-61 (2006).

4. Minakov A.A., van Herwaarden A.W., Wien W., Wurm A., Schick C., Thermochim. Acta, 461, 96-106 (2007).

5. Kanaï J., Grossman J.C., Nano Letters, 7, 1967-1972 (2007)

6. Wiggins P., Gareth Williams J.A., Tozer D.J., J. Chem. Phys., 131, 091101 (2007)

8435-89, Poster Session

Titanium dioxide nanostructure synthesized by sol-gel for organic solar cells using natural dyes extracted from black and red sticky rice

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Nanocrystalline semiconductor metal oxides have achieved a great importance in our industrial world today. They may be defined as metal oxides with crystal size between 1 and 100 nm. TiO2 nanosize particles have attracted significant interest of materials scientists and physicists due to their special properties and have attained a great importance in several technological applications such as photocatalysis, sensors, solar cells and memory devices. TiO2 nanoparticles can be produced by a variety of techniques ranging from simple chemical to mechanical to vacuum methods, including many variants of physical and chemical vapor deposition techniques. In the present research work we report the synthesis of TiO2 nanoparticles by Sol-Gel technique. The characterization of particles was carried out by XRD, SEM and XRF techniques. The importance and applications of these nanoparticles for solar cells are also discussed in this work.

The titania nanoparticles were synthesized by drop wise addition of titanium tetrachloride: TiCl4 in ethanol and Pluronic P2243-250G. The reaction was performed at room temperature while stirring under a fume hood due to the large amount of Cl2 and HCl gases evolved in this re-action. The resulting yellow solution was allowed to rest and cool back to room temperature as the gas evolution ceased. The suspensions obtained were dried in an oven for several hours at 80 oC until amorphous and dried TiO2 particles were obtained. The obtained powder samples were cal-cined for one hour in a box furnace at temperature ranging from 375 to 600 oC in an ambient at-mosphere. XRD patterns were recorded on as prepared and calcined samples using a Bruker D8 Advance diffractometer equipped with a graphite crystal monochromator, operating with a Cu an-ode and a sealed X-ray tube. The 2Θ scans were recorded at several resolutions using Cu Kα ra-diation of wavelength 1.54 Å in the range 20-80o with 0.05o step size. The chemical composition of the samples was determined by X-ray Fluorescence Spectroscopy (XRF) using a Bruker AXS S2 Ranger. SEM FEI has been used to determine nanoparticle size of TiO2. The absorption of an-thocyanins extracted from the black and red rice was conducted using a Spectrophotometer UV-Visible Shimadzu 1601 PC.

Annealing resulted in diffraction peaks related only to the anatase and rutile polymorphs of TiO2. From 375 oC to 600 oC only peaks related to anatase structure were evident. Above 600 oC rutile peaks started to appear and a mixture of both the anatase and rutile phases of TiO2 existed up to 800 oC. At 850 oC, the XRD pattern showed a complete transformation from anatase to rutile. From the XRD data, it is evident that the crystallite size increases with increasing calcinations temperature and that the diffraction peaks become intense and their FWHM gradually became narrow suggesting an increase in particles size and increase in the amount of the pertinent phase. The anatase (101) peak was used to determine the grain size by Scherer's formula. It was found that the absorption peak of black rice extract is about 520 nm while that of red rice extract is about 480 nm. However, the spectra range of the black rice is wider than those of the red rice. The difference in the absorption characteristics is due to the different type of anthocyanins and colors of the extracts. It was reported that anthocyanin obtained from black rice is ternatin while those from red rice are delphinidin and cyanidin complexes. An absorption peak at high wavelength of black rice extract is responsible for its blue color.

8435-93, Poster Session

Equilibrium component composition and structure of nanometer cyanine dye layers and their photoinduced modification

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Thin organic layers and films are used in a variety of areas, from scientific research, such as tunnelling effects between superlattices and modelling cell membranes, to practical applications including nonlinear optics, nanolithography.

We study the component composition of cyanine dye layers on different substrates (glass, mica, and sapphire) by the absorption spectroscopy. We found that the molecular layer contains isomers of the molecules being coated and aggregated components (dimers and J-aggregates). The relative concentrations of the components depend on the structure of dye and its surface concentration.

The single laser pulses of several nanosecond duration lead to irreversible changes in the structure of molecular nanolayers and result in the change of the relative concentrations of the layer components.

Two types of the spatial orientation of the nanocomponents with different orientations with respect to the surface are formed. One of these types of the orientation transforms into another type under the action of pulsed laser radiation.

The above changes were found for all the dielectric substrates studied.

8435-13, Session 3

Controlling recombination and improving the photocurrent in polymer: fullerene blends with molecular doping

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The efficiency of organic solar cells is directly influenced by recombination at the donor-acceptor interface. Following photoinduced charge transfer between donor and acceptor, electrons and holes are still coulombically bound resulting in the formation of charge transfer excitons (CTEs).1 Recombination over the CTE is known to play a crucial role in solar cells, limiting the open circuit voltage and the short circuit current.2 Increasing charge carrier mobility locally near the donor-acceptor interface by inducing long range ordering effectively reduces CTE recombination, which is correlated with an increase in the photocurrent and the solar cell efficiency 3,4. In this contribution, we propose a novel strategy to partially overcome recombination due to CTEs. The electronic properties of the conjugated polymer poly[2,6-(4,4-bis-(2-ethylhexyl)-4H-cyclopenta[2,1-b;3,4-b']dithiophene)-alt-4,7-(2,1,3-benzothiadiazole)] (PCPDTBT) are tuned by doping with 2,3,5,6-Tetrafluoro-7,7,8,8-tetracyanoquinodimethane (F4-TCNQ). The excess charge induced by F4-TCNQ fill the tail of states in the highest occupied molecular orbital of the polymer. We employ time resolved photoluminescence and infrared photoinduced absorption spectroscopy to demonstrate how doping results in a decreased population of CTEs and ultrafast enhanced formation of polarons.4 In addition, an increase in the conductivity and a five-fold increase in the hole mobility at low doping concentrations in both the pristine polymer and the PCPDTBT:PCBM blend are demonstrated. Solar cells based on doped blends show increased photocurrents and efficiencies compared to reference devices. The results demonstrate a new approach to improve solar cell efficiency by tuning the efficiency of charge separation at the molecular scale.

References:

1 M. Hallermann, I. Kriegel, E. Da Como, J. M. Berger, E. von Hauff, J. Feldmann, Adv. Funct. Mater. 19, 3662 (2009).

2 M. Hallermann, E. Da Como, J. Feldmann, M. Izquierdo, S. Filippone, N. Martin, S. Juchter, E. von Hauff, Appl. Phys. Lett. 97, 023301 (2010).

3 D. Veldman, Ö. Ipek, S. C. J. Meskers, J. Sweelssen, M. M. Koetse, S. C. Veenstra, J. M. Kroon, S. S. van Bavel, J. Loos, R. A. J. Janssen, J. Am. Chem. Soc. 130 7721 (2008)

4 F. Deschler, E. Da Como, R. Tautz, E. Von Hauff, U. Scherf, J. Feldmann, Phys. Rev. Lett. 107 127402 (2011)

8435-14, Session 3

Electronic structure of organic/oxide interfaces for OPV devices

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Charge carrier transport across organic/organic and hybrid organic/inorganic interfaces plays a central role in the performance of most organic devices. In organic photovoltaic (OPV) cells in particular, the hole-extracting contact on the donor side of the device typically involves large work function transparent conducting electrodes, which have been the subject of intense scrutiny over the past few years. These include transparent conducting oxides (TCO) such as indium-tin or gallium-doped zinc oxides (ITO, Ga:ZnO) or transition metal oxides (TMO) such as molybdenum, tungsten, vanadium or nickel oxides (MoO3, WO3, V2O5, NiOx). This talk examines the formation of some of these films via vacuum evaporation, or via solution or sol-gel deposition. We look at specific interfaces between hole-transport organic materials (HTM), i.e. the donor in an OPV cell, and these TCOs and TMOs, their electronic structure and corresponding hole-injection/extraction efficiency. Simple electrode/organic/electrode “hole-only” devices are fabricated for current-voltage measurements. These comprise an HTM (small molecule or polymer) with the metal oxide as bottom contact and a heavily p-doped layer at the top contact for facile hole-injection. Hole injection/extraction from/to TCOs and TMOs are correlated with the interface electronic structure, and compared with performance achieved with standard ITO and PEDOT:PSS electrodes. Results from “electron only” devices comprised of electron transport materials, TCO and TMO layers are presented and discussed from the view point of the material’s electron-blocking properties. Results are presented on both standard-geometry and inverted OPV cells comprising solution processed NiOx or V2O5. Finally, the electronic structure of oxide/oxide or oxide/organic pairs as possible charge (electron-hole) recombination layers for tandem cells is discussed.

8435-15, Session 3

Molybdenum trioxide as a universal p-dopant for organic hole transporters

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The effects of doping molybdenum trioxide (MoO3) into a wide varieties of organic hole transporters (HTs) are examined. The organic HTs include spiro-TPD, MTDATA, 2TNATA, NPB, rubrene, TPD, TCTA, MADN, and CBP. The HTs chosen possess different energies in their highest occupied molecular orbitals (HOMOs), ranging from about 4.9 to 5.8 eV. In-plane conductivities measurements show that MoO3 is a universal p-dopant as it transforms all HTs from semi-insulators into semiconductors. However, there is no direct correlation between the conductivities and the HOMO energies. Field effect transistor (FET) measurements on the MoO3-doped organic HTs allow us to determine their carrier mobilities. At a doping concentration of 5%, there is a general reduction in the hole mobilties. Combining the mobilities and conductivities data allow us to extract the free carrier concentrations. The hole concentrations vary between 1016-1018cm-3 after doping whereas undoped samples have neglibible hole concentrations. The increase of free carrier concentration is, therefore, the deciding factor in the conductivity enhancement in doped organic HTs. Temperature dependent measurements on field effect mobilities allow us to gauge the energetic disorders of the hopping manifold before and after doping. In all cases, we observe reductions in the energetic disorders after doping. There is no clear correlation between the conductivities of the doped sample and the HOMO energies of the organic HTs.

8435-16, Session 3

Functional interfaces for organic electronic devices characterized by in situ XPS, current voltage measurements, and impedance spectroscopy

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Organic light-emitting diodes (OLEDs) have been considered as promising candidates for display and high-efficiency lighting applications. The injection barrier heights at the interfaces of the organic material and the electrodes are crucial for the efficiency of the device, since charge carriers are injected here.

Indium doped tin oxide (ITO) is widely used in optoelectronic devices as anode material due to the combination of high conductivity with high transmittance and the optimal work function for hole injection into common organic materials like α-NPD. However since transparent OLEDs get more important for both, display and lighting applications, a transparent cathode material is of high interest. Here semi transparent metals or transparent conducting oxides (TCOs) can be used. While the normal interfaces (organic on ITO) have been studied before, there is a lack of data on the inverted interfaces especially with regard to their band alignment and injection properties.

In this contribution we preset a combination of in-situ photoelectron spectroscopy (XPS and UPS), current voltage measurements (IV) and impedance spectroscopy (IS) both performed in vacuum, at the organic TCO interfaces. The investigated interfaces in this work are α-NPD/ITO and BCP/ITO, when ITO is sputterd on top of the organic molecules for providing electrodes in transparent or inverted OLEDs. ITO is deposited by r.f. magnetron sputtering in a face to face alignment without intentional substrate heating. The sputter particle energy (Esp) is decreased [Esp=f(P,d,p...)] for avoiding damage at the soft substrate. The barrier heights measured with XPS are correlated with the in-situ IV and IS results.

No chemical reaction at the interface can be detected with XPS indicating stable organic molecules during the sputtering process. Moreover IV and IS characteristics also confirm stable molecules, since a diode behavior is measurable at a symmetric device consisting of ITO / organic / ITO layers. Doping of the organic layers leads to better injection properties from the ITO electrode. Nevertheless the barrier heights measured with in-situ XPS, in the case of BCP up to 1.5 eV, shows a discrepancy with electrical measurements, since electrons can be injected also at this interface, indicating a smaller barrier height.

8435-17, Session 3

Low temperature sol-gel processing of MoO3 as high work function charge extraction layer in stable and efficient organic solar cells

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For large-scale and high-throughput production of organic solar cells (OSCs), liquid processing of the functional layers is desired. Aside from the active organic layers, inter-layers are typically required to facilitate the extraction of the photo-generated charges. On the anode side, PEDOT:PSS is regularly used. However, aqueous PEDOT:PSS and its acidic nature has been evidenced to be an origin of limited device lifetime. In addition, for novel low-bandgap donor-acceptor polymers with deeper HOMO levels interlayers a higher work function may be required. Transition metal oxides, TMOs, such as V_2O_5 and MoO_3 have been shown to exhibit ultra-high WFs up to 7eV [1]. The unique energetics of these TMOs has so far been accessible mostly for films thermally evaporated in high-vacuum.

Recently, we introduced a room-temperature sol-gel process for V_2O_5 and its application in OSCs. However, the relatively low bandgap of V_2O_5 (2.3 eV) may result in substantial absorption losses. From this point of view, MoO_3 with a larger band gap of 2.9 to 3.1 eV should be preferable.

The liquid processing of MoO_3 was so far realized using nano-particle approach [2] and casting from aqueous solutions [3, 4]. The essential drawbacks of these techniques are either high post-annealing temperatures (275°C) or oxygen plasma treatment (or both). Also, in case of NP-dispersions particle aggregation is found to result in rough layers.

In this work we report liquid processed smooth (3 nm, rms) MoO_3 layers prepared from Bis(2,4-pentanedionato)molybdenum(VI)dioxide/isopropanol solution via hydrolysis in ambient air. As opposed to previous works, only a low-temperature post annealing step at 150°C is required to remove surface adsorbates before deposition of the active layer. OSCs with sol-gel MoO_3 based on P3HT:PCBM demonstrate high power conversion efficiency of 3.3%, comparable to control devices with PEDOT:PSS, but significantly enhanced stability at ambient air.

1. J. Meyer, K. Zilberberg, T. Riedl, and A. Kahn, Journal of Applied Physics 2011, 110, 033710 (2011).

2. J. Meyer, R. Khalandovsky, P. Görrn, and A. Kahn, Adv. Mater. 2010, DOI:10.1002/adma.201003065).

3. F. Liu, Sh. Shao, X. Guo, Y. Zhao, Zh. Xie, Solar Energy Materials & Solar Cells 2010, 94, 842-845.

4. C. Girotto, E. Voroshazi, D. Cheyns, P. Heremans, and B. P. Rand, Solution-processed MoO_3 thin films as a hole-injection layer for organic solar cells, ACS Appl. Mater. Interfaces 2011, 3, 9, 3244-3247.

8435-18, Session 3

Low-temperature fabrication of ZnO-based inverted organic solar cells

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We demonstrate fabrication of inverted organic solar cells (IOSCs), where a ZnO electron-transport layer is deposited by a low-temperature (5 hrs). If combined with solution-processed hole-transporting and cathode layers, the aqueous method for ZnO deposition is particularly well-suited for low-cost, large-area fabrication of IOSCs on flexible substrates. We discuss the effects of various processing conditions, such as the ambient of the ZnO precursor spin coating and subsequent annealing, on the quality of ZnO films and the device performance.

8435-19, Session 4

Polaron pair generation yield in low-bandgap donor-acceptor copolymers for photovoltaics

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The most recent advances in the power conversion efficiency of organic solar cells consider the design of low-bangap copolymers with an extended absorption in the near infrared. These materials, based on the donor-acceptor concept, i.e. with moieties of different electron affinity alternating on the chain, have attracted a considerable interest. The low bandgap offers optimal light-harvesting characteristics and has inspired much work towards the achievement of record power-conversion efficiencies in solar cells. Here, we report how the chemical structure of donor and acceptor moieties controls one of the primary steps in organic photovoltaics, i.e. the photogeneration of polaron pairs. In our study we consider the polymers as thin films in the pristine form and determine that copolymers with adjacent donors and acceptors moieties show yields of polaron pair formation up to 40% of the initial photoexcitations. This yield has a weak dependence, ±2%, on the difference in electron affinity, but a more pronounced one on the mutual separation, in which case it drops to ~30%. Conjugated spacers, used to separate the donor and acceptor center of masses, have the beneficial role of increasing the recombination time by almost an order of magnitude. The results when compared to homopolymers such as poly(3-hexylthiophene) show that donor-acceptor copolymers have a larger polaron pair yield but shorter recombination times. These findings are discussed considering the intrachain energetic disorder of these novel materials.

8435-20, Session 4

Exploring the exciton dissociation process at a donor-acceptor heterojunction in both time and space via an induced Stark shift

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Charge separation at a donor-acceptor heterojunction is central to the operation of all efficient organic photovoltaic cells, yet the details of how this process transpires remain unclear. One of the challenges in developing a more thorough understanding is to develop methods that experimentally monitor the entire charge separation process, from the initial photoinduced charge transfer event to the complete dissociation of the carrier pair. Transient absorption spectroscopic approaches are useful in studying kinetic aspects, such as the formation and decay of charge transfer states and free polarons, however, the crucial intervening evolution of bound carrier pairs is not directly observable and hence is left to inference and modeling.

Here, we demonstrate a novel technique to observe charge separation at a heterojunction in both time and space with sub-picosecond resolution based on the Stark shift induced in a nearby 'probe' layer of molecular J-aggregates. We study a typical small molecule planar heterojunction involving the donor 4-4′-bis[N-(1-naphthyl)-N-phenyl-amino]biphenyl (NPD) and the fullerene acceptor C60. Following selective excitation of C60 in the structure C60/NPD/J-aggregate, holes resulting from exciton dissociation at the donor-acceptor interface are transported through the NPD layer toward the J-aggregate, where their electric field induces a measurable Stark shift owing to the large polarizability of the J-aggregate exciton band. Thus, by varying the NPD layer thickness, we time-resolve the displacement of holes from the donor-acceptor interface at varying stages in the dissociation process, providing new insight into the evolution of geminate pairs on the nanosecond and sub-ns timescale.

8435-21, Session 4

Modelling exciton and charge carrier dynamics in organic semiconductors: a quantum chemical view

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Although organic electronic devices like organic light emitting diodes, photovoltaic cells or field effect transistors have reached a very promising status, a comprehensive molecular picture of device operation is still under development. A molecular picture requires atomistic thin film morphologies, expressions for rate equations, transport parameters (quantum mechanical and classical) and finally lattice-based simulation techniques in order to link microscopic parameters to macroscopic observables like mobilities or diffusion constants.

As an example for the simulation of charge carrier mobilities we will discuss the transport properties of a BASF host material for deep blue phosphorescent OLEDs. The study includes realistic disordered morphologies, polarized site energies to describe diagonal disorder, quantum chemically calculated transfer integrals for the off-diagonal disorder, inner sphere reorganization energies and an approximative scheme for outer sphere reorganization energies. Intermolecular transfer rates were calculated via Marcus-theory and mobilties were simulated via kinetic Monte Carlo simulations. An analysis of charge transport in molecular terms will be given.

To give an insight into exciton dissociation at interfaces we will discuss the example pentacene/C60. An electrostatic embedding scheme (QM/MM) will be used here, which allows for a high level description of a small interface region by accurate ab initio methods like CC2, whereas the environment will be described via a polarizable force field. Different geometric arrangements of the interface and the impact on exciton dissociation will be discussed.

8435-22, Session 4

Influence of defects in organic materials for organic solar cells

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The existence of defects in organic semiconductors has long been considered a critical concept controlling device performance [1,2]. But even with the rapid progress in organic solar cells (OSCs) there is still a significant gap in our knowledge about the role of defects, their basic origin and impact. That is, the physical mechanism responsible for the formation of defects and the correlation with the OSC performance. Popular theoretical models do not acknowledge their existence, even though in conjugated polymers the presence of defects strongly influences the OSC performance [3]. Paradoxically the presence of defects isn't detrimental. In fact, due to the 'hopping' nature of charge transport in these materials, OSCs made with defect-laden materials are known to achieve some of the highest efficiencies. Therefore, understanding the impact of defects on device performance, and applying this knowledge towards making better devices (i.e. defect engineering) is of significant importance to the field.

In our paper we will discuss the role of defects in a number of organic materials used for OSCs by employing Deep Level Transient Spectroscopy (DLTS) [4]. Having been developed for inorganic semiconductors, DLTS is a powerful tool to study defects. It allows the type of defect (i.e. electron or hole) to be distinguished and is able access the 'deep' traps responsible for trapping free carriers that can have a significant impact on the electrical performance of devices. In this study, we characterise the defects in P3HT:[C60]PCBM and PCDTBT:[C70]PCBM bulk heterojunction OSCs as classic examples of current state-of-the-art OSC technology.

We observe a number of interesting phenomena. In particular, that the density of deep traps in PCDTBT is in fact an order of magnitude lower than in P3HT. This could help to account for the excellent performance of PCDTBT based OSCs, besides the improvement afforded by lower optical gap and the increased open-circuit voltage. Additionally, we will report on the influence of processing condition (i.e. annealing) on the defect density and activation energy in P3HT. We find that annealing the active layer before electrode deposition reduces the deep defect density by an order of magnitude, and this accounts in part for the importance of annealing the devices for improved device performance.

Overall, the above results, in conjunction with recent works such as Ref. [5] provide the growing motivation for establishing the idea of defect engineering in OSC. Defect engineering, coupled with material innovation, will be important in increasing the efficiencies to deliver state-of-the-art OSCs.

[1] Organic Semiconductors, Wiley (1967)

[2] Phys. Rev. B 55, 9590 (1997)

[3] Soft Matter 5, 2985 (2009)

[4] J. Appl. Phys. 45, 3023 (1974)

[5] Adv. Energy Mater. 1, 655 (2011)

8435-23, Session 4

Comparing the degree of molecular order in P3HS and P3HT-based photovoltaic films: resonant Raman spectroscopy as a unique structural probe

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We study the degree of molecular order in poly(3-hexylthiophene) (P3HT), poly(3-selenophene) (P3HS), P3HT: [6,6]-phenyl-C61-butyric acid methyl ester (PCBM) and P3HS:PCBM photovoltaic films by absorption spectroscopy, X-ray diffraction, Raman spectroscopy, optical microscopy and density functional theory. We find that substituting the sulphur (S) atoms at the thiophene rings of P3HT by heavier selenium (Se) atoms (P3HS) lead to an increase in polymer chain planarity, which favour the formation of highly ordered phase/crystallization. Interestingly, we find that the amorphous part of P3HS in P3HS homopolymer and P3HS:PCBM blend films is more disordered than that of P3HT in P3HT homopolymer and P3HT:PCBM blend films by Resonant Raman spectroscopy (RRS). This is evidenced by the Resonant Raman spectra (symmetry stretch C=C mode) of P3HS-based films having more asymmetry peak shape and larger Raman dispersion (shift of the Raman peak position with excitation wavelength) than that of P3HT-based films. This highly disordered P3HS phase can mix better with PCBM molecules than that of P3HT during thermal annealing, suppressing formation of the micro-sized PCBM aggregates. We proposed structural models for the pristine and annealed P3HS:PCBM and P3HT:PCBM blend films, in which the P3HS is more crystalline in the blend than P3HT but the amorphous part of P3HS in the blends is more disordered than that of P3HT in the blends. The structural models agree well with the device performance of P3HS:PCBM and P3HT:PCBM solar cells (both pristine and annealed). Our studies provide significant insight into the effect of the Se substitution on the structural properties of the films. Importantly, we find that RRS is an important tool to gain a more complete understanding of the degree of molecular order in P3HS and P3HT-related photovoltaic blend films, particularly in the amorphous phase which can be crucial.

8435-24, Session 5

Thermodynamic efficiency limit of molecular donor-acceptor solar cells and its application to diindenoperylene (DIP)-based devices

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In contrast to conventional (inorganic) semiconductor photovoltaic cells, the working mechanism of their organic counterparts is markedly different, most importantly due to the excitonic nature of photo-excitations in organic semiconductors. Using them as photovoltaic materials thus requires finding ways for an efficient dissociation of excitons with binding energies of the order of 0.5 eV into free charge carriers that can deliver an electrical current into the external circuit. In this context, the well-established donor-acceptor (D/A) concept enabling photo-induced charge transfer between two partners with suitable energy level alignment has proven extremely successful. Nevertheless, the introduction of such a hetero-junction is accompanied with additional energy losses as compared to an inorganic homo-junction cell, owing to the presence of a charge-transfer (CT) state at the D/A interface.

Based on the principle of detailed balance we have developed a modified Shockley-Queisser theory including the effects of interfacial CT states that allows for a quantitative assessment of the thermodynamic efficiency limits of molecular D/A solar cells. Key parameters, apart from the optical gap of the absorber material, entering into the model are the energy and relative absorption strength of the CT state. We demonstrate how the open-circuit voltage and thus the power conversion efficiency are affected by different parameter values. Furthermore, we show that temperature dependent device characteristics can serve to determine the CT energy, and thus the upper limit of Voc for a given D/A combination, as well as to quantify non-radiative recombination losses. The model is applied to diindenoperylene (DIP)-based photovoltaic devices, where open-circuit voltages between 0.9 and 1.4V, depending on the partner, have recently been reported [1,2].

[1] J. Wagner et al., Adv. Funct. Mater. 20, 4295-4303 (2010)

[2] U. Hörmann et al., phys. stat. sol. RRL 5, 241-243 (2011)

8435-25, Session 5

Small molecular organic photovoltaic cells with exciton blocking layer at anode interface for improved device performance

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We demonstrate enhanced power conversion efficiency (ηPCE) for small molecular-based organic photovoltaic cells with an exciton blocking layer (ExBL) at the anode/donor interface. Although poly(3,4-ethylenedioxythiophene):poly(4-styrene sulfonate) (PEDOT:PSS) films are widely used as anodic buffer layers, they also act as exciton quenchers. To prevent exciton quenching, we introduced a tris[4-(5-phenyl thiophen-2-yl)phenyl]amine layer between the donor and the PEDOT:PSS layer and clarified its effect. By a combination of dual ExBLs at both the anode and cathode sides, we achieved significantly enhanced short circuit current and ηPCE values; the highest ηPCE=5.24% was obtained by optimizing the device parameters.

8435-26, Session 5

Novel methods for morphology control of small molecule organic thin films

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We present methods for nanostructuring organic thin films with columnar morphologies suitable for organic photovoltaic (OPV) devices. Using the glancing angle deposition (GLAD) technique, we can fabricate a variety of high surface area morphologies of metal phthalocyanine (MPc) materials that are used in the active layer of OPV devices. We leverage this capability with block copolymer surface patterning techniques to achieve perfectly periodic columnar arrays while providing additional control over column dimensions and spacing. Our investigation employs hexagonal seed patterns on silicon with a variety of seed spacings and we find that pattern resemblance is limited to patterns with 40 nm seed spacing, depending on film thickness and the GLAD parameters used during film growth. Results from patterning ITO in a similar manner for OPV device integration will be shown. In addition, we discuss the challenges of and our solutions to integrating columnar film morphologies into devices. To complete the active layer in an OPV device, for example, we fill a nanostructured ZnPc film by spin-coating with PCBM, which provides more complete filling than evaporation of C60. Spin speed, solution concentration and solvent choice are the critical metrics used to optimize device performance. Our best results are achieved when using dichlorobenzene (DCB) as the PCBM solvent, where we get an average efficiency of 2.86 ± 0.09%, which is a 25% improvement over devices made using chlorobenzene (CB) as the PCBM solvent. Analysis of the active layer via SIMS reveals a greater degree of overlap between ZnPc and PCBM when using DCB instead of CB. Thus, our approach offers a pathway to further optimization of small molecule OPV devices by providing control over the permeation of donor and acceptor materials into one another at their interface.

8435-27, Session 5

Modelling of organic triple-junction solar cells

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In order for organic bulk heterojunction solar cells to compete with the traditional inorganic cells, higher power conversion efficiencies are desirable. A characteristic of organic solar cells is their narrow absorption window, compared to the absorption band of inorganic semiconductors. A possible way to capture a wider band of the solar spectrum - and thus increasing the power conversion efficiency - is using two or more solar cells with different bandgaps in a row, referred to as a multi-junction solar cell. In this article, we study the theoretical efficiency potential of three organic cells in a row, i.e. a triple-junction. We study the influence of the energy levels of donor and acceptor, as well as different absorption windows of the subcells. We not only study the light harvesting potential of the usual monolithic configuration, but also consider a stacked set-up. Ideal material characteristics are obtained from these calculations, giving an idea of how the ideal organic triple-junction cell should look like.
An interesting result is that it is not necessary to develop photovoltaic organic materials with an absorption window broader than 300 nm for triple-junctions, because hardly any efficiency gain can be achieved by a broader absorption window. Furthermore, for a stacked organic cell, the subcells do not necessarily need a large absorption window. This does not apply for the monolithic cell. As soon as one subcell has a small absorption window, the efficiency decreases rapidly. Finally, we make realistic assumptions to predict efficiencies obtainable in the near future and calculate the upper-limit. We compare our results with fully organic multi-junction cells fabricated by several research institutes, and thus with current state of technology.

8435-28, Session 5

Solution processed graded absorber layers for a fast and material-saving layer thickness optimization in polymer photovoltaic devices

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The record efficiency of organic solar cells recently exceeded 9%. To further improve the harvesting of light, new materials will have to be developed. Unfortunately, new materials are usually synthesized on a milligram scale in order to prove their functionality. When optimizing photovoltaic devices comprising these new absorbers, the material availability does not allow for an extensive processing parameter optimization.

In this work we present a facile route to an efficient experimental screening of new materials and layer thickness optimization in solution processable polymer photovoltaic devices. Therefore, we developed a method of fabricating solar cells with a graded active layer thickness based on a doctor blading technique. A spatially resolved mapping of the solar cell short circuit current density for different light absorbing polymers under white light allows for a quick conclusion about the optimum active layer thickness within the device. When plotting the short circuit current density versus the local active layer thickness, the influence of the thin film interference pattern within the device becomes apparent. The measured short circuit current densities are in very good accordance with optoelectronic device simulations for all layer thicknesses.

This technique is also applicable to other functional layers within the organic solar cell and allows for a fast material-saving functional layer thickness optimization.

8435-29, Session 5

Visualizing vertical phase separation in films of polymer: fullerene blends

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Morphology control has been one major key to the recent improvements in energy conversion efficiency of polymer-based photovoltaic devices. Such devices consist of solution-cast thin films of electron donor and electron acceptor molecules mixed with one another, a so-called bulk heterojunction. This molecular distribution has strong effect on the charge generation processes in the solar cell, such as the separation of excitons into mobile charges at the donor/acceptor interface and the transport of these mobile charges to the electrodes. When a thin film is prepared by spincoating a blend of a conjugated polymer and the fullerene-based acceptor material, PCBM, demixing determines the nanostructure in the film, which is influenced by the polymer-fullerene-solvent interactions, the molecules' tendency to self-organise, and the kinetics of the film formation. During spincoating, characterized by rapid solvent evaporation, the kinetics of nucleation and of two-phase separation compete. The formation of lamellar phases and vertical concentration gradients has been reported for several blend systems, among which P3HT:PCBM, APFO3:PCBM.[1-4] Characterization of the composition and molecular orientation at these interfaces is a major challenge, because very few techniques exhibit both the chemical contrast and the lateral or depth resolution required to unveil the nanostructure of these bulk heterojunctions. We have used a combination of Atomic Force Microscopy (AFM), dynamic Secondary Ion Mass Spectrometry (d-SIMS), Near-Edge Absorption Fine Structure (NEXAFS) spectroscopy, and recently Neutron Reflectometry (NR), to probe the surface and bulk composition of polymer:fullerene blends. Differences in composition between surface and sub-surface are observed and form strong evidence for vertical phase separation. The dependence of the resonance peaks on the angle of incidence of the X-rays yields additional information about molecular orientation.

References

[1] C.M. Björström, A. Bernasik, J. Rysz, A. Budkowski, S. Nilsson, M. Svensson, M. R. Andersson, K. O. Magnusson, E. Moons, J. Phys.: Condens. Matter 2005, 17, L529.

[2] D. S. Germack, C. K. Chan, B. H. Hamadani, L. J. Richter, D. A. Fischer, D. J. Gundlach, D. M. DeLongchamp Appl. Phys. Lett. 2009, 94, 233303.

[3] B. Xue, B. Vaughan, C.-H. Poh, K. B. Burke, L. Thomsen, A. Stapleton, X. Zhou, G.W. Bryant, W. Belcher, P. C. Dastoor J. Phys. Chem. 2010, 114, 1.

[4] A. S. Anselmo, L. Lindgren, J. Rysz, A. Bernasik, A. Budkowski, M. R. Andersson, K. Svensson, J. van Stam, E. Moons Chem. Mater. 2011, 23, 2295.

8435-30, Session 5

Crystallization kinetics and morphology relations on thermally annealed bulk heterojunction solar cell blends studied by rapid heat cool calorimetry (RHC)

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Post-production annealing treatments increase the efficiency of bulk heterojunction solar cells by forming a well-ordered morphology that creates better transportation pathways for charges to flow towards the corresponding electrodes. In general, the thermal annealing treatments increase the crystallinity of the components, leading to a nanoscale phase separated morphology, and consequently increase the device efficiency [1, 2]. For an optimal efficiency and performance of the solar cells, a finely-dispersed phase morphology, having a dimension of 5-20 nm dimensions, is thought to be required [3]. To attain this, the thermal annealing conditions need to be tuned carefully. Too high temperatures or too long annealing times can induce a decrease of the efficiency due to the overgrowth of the crystals [4, 5].

In terms of the long-term stability of the solar cell devices; keeping the desired morphology steady is as important as fine-tuning of both polymer and fullerene chemistries. Having lower glass transition temperatures (Tg) than the maximum device operation temperature of 80°C, the blends keep having the mobility which might drive the phase separated morphology further and thus, lower the efficiency in the course of time.

Both for optimizing the desired morphology and also for keeping it constant during operation, the crystallization kinetics of the polymer: fullerene blends during annealing should be investigated. Such an investigation requires avoiding fast crystallization processes during heating and cooling [6] which can only succeed using fast-scanning techniques such as Rapid Heating Cooling Calorimetry (RHC). RHC, recently developed by TA Instruments, is a fast DSC for high scanning rates of up to 2000°C/min [7]. Reorganization during heating can be avoided via the fast heating rates of the instrument, and using the high cooling rates, crystallization during cooling can be avoided and a glassy blend can be achieved. Hence, it becomes possible to crystallize isothermally at temperatures closer to Tg for materials it was not possible for previously.

In this study, the crystallization kinetics and morphology relations of the thermally annealed polymer: fullerene bulk heterojunction solar cell blends will be investigated by means of RHC.

REFERENCES:

1. Erb T, Zhokhavets U, Gobsch G, Raleva S, Stuhn B, Schilinsky P, Waldauf C, and Brabec CJ. Advanced Functional Materials 2005;15(7):1193-1196.

2. Nguyen LH, Hoppe H, Erb T, Gunes S, Gobsch G, and Sariciftci NS. Advanced Functional Materials 2007;17(7):1071-1078.

3. Thompson BC and Frechet JMJ. Angewandte Chemie-International Edition 2008;47(1):58-77.

4. Jo J, Kim SS, Na SI, Yu BK, and Kim DY. Advanced Functional Materials 2009;19(6):866-874.

5. Bertho S, Janssen G, Cleij TJ, Conings B, Moons W, Gadisa A, D'Haen J, Goovaerts E, Lutsen L, Manca J, and Vanderzande D. Solar Energy Materials and Solar Cells 2008;92(7):753-760.

6. Demir F, Van den Brande N, Van Mele B, Bertho S, Vanderzande D, Manca J, and Van Assche G. Journal of Thermal Analysis and Calorimetry 2011;105(3):845-849.

7. Danley RL, Caulfield PA, and Aubuchon SR. American Laboratory 2008;40(1):9-11.

8435-31, Session 6

Dielectric-metal-dielectric multilayer transparent electrodes for versatile transparent organic electronics

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Transparent organic electronics or optoelectronics are attracting a significant amount of interest as it can offer unique functionalities not available from conventional semiconductor technologies such as see-through displays, smart and/ or energy-harvesting windows, and invisible electronic devices that may provide some essential roles while being seamlessly integrated with various products or structures.

In this talk, we investigate a device architecture based on transparent conductive oxides (TCOs) /organic semiconductors / dielectric-metal-dielectric (DMD) multilayer electrodes (MTEs) as an effective, versatile platform for transparent organic electronics in the area encompassing organic light-emitting diodes (OLEDs), organic solar cells (OSCs), and organic thin-film transistors.

After briefly reviewing the principle of operation of DMD-based MTEs, we demonstrate their potential advantages over the established transparent electrode technologies in various case studies: First of all, highly transparent OLEDs are presented which exhibit highly asymmetric light emitting characteristics which can be useful in many practical applications of transparent displays and lighting. Then, the similar asymmetric optical properties are utilized to realize see-through organic solar cells with efficiency reaching up to 80-90% of the opaque equivalents. Finally, we present a high performance, highly transparent organic thin-film transistor in which source and drain electrodes participate as a part of the dielectric-metal-dielectric structure. The role of the inner dielectric layer is also discussed in terms of carrier injection enhancement.

Overall, device optimization strategies and key engineering factors are discussed in details.

8435-32, Session 6

Ray-optical light trapping in organic solar cells

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Organic solar cells (OSCs) have drawn much attention because they can be low-cost, lightweight, and flexible. The main drawback of thin-film solar cells, however, is relatively low light absorption due to their thin active layers. Therefore, it is necessary to develop proper light trapping schemes to increase the average path-length of incident ray, and hence the power conversion efficiency. Theoretical path length enhancement limit with light trapping in solar cells is known to be n^2/sin^2((θa/2), where n is a refractive index of medium, and θa is an acceptance angle [1, 2]. However, as the active layers of organic solar cells are so thin that they cannot be textured for efficient ray-optical light trapping, optical components should be placed on a glass substrate. But, rather small refractive index of glass (n=1.5) makes the enhancement much smaller than that of silicon solar cells (n=3.5). A reduced acceptance angle can compensate the small enhancement from the low refractive index, since the sun is always on its orbit during the day and the height of the sun varies annually only within ±23.5 degree. We found that with 47 degree of the acceptance angle, 17.5% of power conversion efficiency enhancements are expected for OSCs using PCPDTBT:PCBM. We also found that light trapping is effective in small molecular OSCs. Because bilayer small molecular OSCs show strong trade-off between internal quantum efficiency (IQE) and absorption by the layer thicknesses, we can reduce the thickness of the active layers to increase IQE while maintaining high absorption through light trapping. The short-circuit current of our small molecular OSCs using CuPc/C60 as active materials is increased from 6.7mA/cm^2 up to 14.9 mA/cm^2. We will propose several configurations of thin-film solar cells including texturing, V-shape, and 1D concentrator array to implement the above-mentioned schemes. Also, we will present simulation results combining both ray-optics and transfer-matrix methods.

[1] E. Yablonovitch, J. Opt. Soc. Am., A 72, 899 (1982).

[2] P. Campbell and M. A. Green, IEEE Trans. Electron. Dev., 33, 234 (1986).

8435-33, Session 6

A simple way to trap photons: textured films on the back side of organic solar cells

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Light trapping schemes have been intensively studied for organic solar cells (OSCs) to overcome the limited absorption associated with their thin photoactive layers. Many of the previous works either involved a direct modification of internal layer structures or a sophisticated nanofabrication. In such cases, however, a unwanted compromise in their electrical properties or added fabrication complexity and cost can often be accompanied. Hence, we here explore simple light-trapping enhancement (LTE) configurations in which a structural modification is given only to the backside of the substrates thereby avoiding a direct influence on the electrical properties of devices.

An example includes an LTE scheme in which a film with a one-dimensional periodic array of V-grooves with a vertex angle of 90 degree and a period of 50um texturing is laminated on to the back of the substrates. When the proposed structure is prepared using poly(dimethylsiloxane) (PDMS) by replicating an optical film (PTX338, Shinwha intertek) used in liquid crystal displays, a consistent enhancement of approx. 8% in short-circuit current density (Jsc) is demonstrated in poly(3-hexylthiophene):1-(2-methoxycarbonyl)propyl-1-phenyl[6,6]C61 (P3HT:PCBM60)-based OSCs without affecting other parameters such as open circuit voltage and fill factor.

A simulation method, which adopts both geometrical race tracing and wave-optic transfer-matrix formalism, is also provided so that one can analyze the optical properties of OSCs with such LTE structure and eventually to optimize their structure. Various potential LTE structures such as lens arrays and ground surfaces are compared and analyzed while varying the critical parameters of each of the structure. Applications to OSCs with other emerging organic semiconductors will also be discussed.

8435-34, Session 6

Combined effects of organic capping layer and enhanced micro-cavity on bi-directional organic light-emitting diodes

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We report on highly enhanced and controlled light outcoupling of bi-directional organic light-emitting diodes (Bi-OLEDs) by introduction of an enhanced micro-cavity structure as well as an organic dielectric capping layer (OC).

Previously, we have reported that the introduction of an additional OC on top of the Ag cathode is an effective method to control the bottom to top ratio as well as to enhance the efficiency towards top emission.[1] However, this additional OC does not show a large influence on overall efficiency (i.e. sum of top and bottom side emission) enhancement because most of the light from devices is emitted dominantly toward the bottom side. Recently, we have developed Bi-OLEDs structure that have balanced light emission for both the bottom and top side (i.e. a unitary ratio of bottom and top side emission) by employing enhanced micro-cavities using an inserted thin semi-transparent Ag layer on top of the ITO anode.[2]

Combining both OC and micro-cavity effects, we find that the overall external quantum as well as current efficiency can be greatly enhanced. Especially, the current efficiency with an appropriate thickness of OC is almost 1.75 times larger value than that of the reference device without OC. We also find that the OC effect with the inserted Ag layer shows much stronger influence on the light-emitting performance of our Bi-OLEDs. Moreover, we investigate the significant changes of optical properties such as the electroluminescence (EL) as well as the spectral angular dependent emission characteristics of our devices depending on the variation of the structure. Finally, we analyze our devices with a numerical optical model calculating the flux of outcoupled photons, and compare theoretical predictions with our experimental results.

References

[1] J. Lee, S. Hofmann, M. Furno, M. Thomschke, Y. H. Kim, B. Lüssem, and K. Leo, Optics Letters, 2011, 36, 1443

[2] J. Lee, S. Hofmann, M. Thomschke, M. Furno, Y. H. Kim, B. Lüssem, and K. Leo, Optics Letters, 2011, 36, 2931

8435-35, Session 6

Semi-transparent small molecule organic solar cells with laminated carbon nanotube top electrodes

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Semi-transparent organic solar cells (STOPV) have attracted great attention because of their versatility and the attractive possibilities of installation on windows, cars, and other architectural building elements. For STOPVs, an efficient, transparent, conductive top electrode is of great importance. Any damage of underlying organic layers during the deposition of the top contact layer is a critical issue and needs to be avoided for practical semi-transparent device applications. Although metal oxides, conducting polymers, silver nanowires, and thin metal layers have been adopted as a top electrode for STOPVs and semi-transparent organic light emitting diodes (OLED), the application is being still considered challenging.

We demonstrate STOPVs based on ZnPc : C60 bulk heterojunction with free standing carbon nanotubes (f-CNT) top electrodes deposited by an orthogonal liquid solution assisted self-laminating process. The fabricated devices show relatively high fill factors of up to 60 % and competitive efficiencies of up to 1.5 %. All devices show very low leakage currents without any additional smoothing layers. These results indicate that the f-CNT lamination process can successfully avoid the damage of underlying organic layers. Furthermore, the STOPVs with f-CNTs show better long-term stability compared to the reference device with a metal top electrode, attributed to the oxidation-free CNT top electrode. The optimization of the device stack is systematically investigated with respect to the optical spacer effect, supported by optical simulations. This result demonstrates that the geometry of STOSCs, including a porous, laminated top electrode, can be optimized by using conventional transfer-matrix theory, assuming top electrodes as a homogeneous layer without optical scattering. The results strongly indicate that STOPVs with f-CNT top electrodes and an optimized thin film stack are highly promising for STOPVs with simple, cheap, and damage-free processing and scalability for roll-to-roll processing and large area applications.

References

[1] M. Zhang, S. Fang, A.A. Zakhidov, S.B. Lee, A.E. Aliev, C.D. Williams, K.R. Atkinson, and R.H. Baughman, Science, 2005, 309, 1215

[2] Y.H. Kim, L. Müller-Meskamp, A. A. Zakhidov, C. Sachse, J. Meiss, J. Bikova, A. Cook, A. A. Zakhidov, and K. Leo, Solar Energy Materials and Solar Cells, 2011, in press, doi:10.1016/j.solmat.2011.10.001

8435-36, Session 6

Solid state efficient low-power photon up-conversion in bicomponent organic systems

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People working on renewable energy sources have been trying to up-convert the solar spectrum to recover low-energy photons not exploited by photovoltaic and photocatalytic devices. In the last years, a new strategy to obtain up-conversion (UC) at ultralow excitation intensities and with non-coherent radiation has been pursued, based on sensitization by energy transfer (ET) of metastable triplet excitons and their annihilation (TTA), leading to radiative higher energy singlet states. Efficient UC (up to 20%) has been demonstrated in liquid systems at excitation intensities as low as 0.1 mW/cm^2 [1]. Despite these results, the fabrication of devices suitable for applications appears still far, since it is difficult to obtain same performances in solid systems due to the lack of large molecular mobility in solution which strongly reduces diffusion controlled TTA efficiency. We report about two strategies to reach good UC efficiencies at solid state. i) We embedded a combination of donor-acceptor dyes within polymeric nanoparticles that act as a container. Since each nanoparticle behaves as an isolated converting unit, they can be dispersed in a liquid solvent, used as a dopant in polymeric matrices or employed to produce drop-cast films, preserving their intrinsic efficiency (≈3%) and allowing the tuning of the doped-material optical density [2]. ii) To emulate the fluid environment of a solution, we select a low Tg polymeric matrix as host for the up-converting dyes. Thus, the short triplet excition diffusion length negative effect is counterbalanced by the molecular diffusion within the matrix, which at room temperature behaves as a viscous fluid. The beneficial effect of this even small molecular mobility permits to obtain efficiency ≈17% in a bulky sample, with excitation irradiance not far from the solar irradiance. Positive and negative aspects of both approaches will be illustrated, in order to estimate potential applications of this kind of photoactive materials.

[1] T. N. Singh-Rachford and F. N. Castellano, Coord. Chem. Rev., 2010, 254, 2560-2573.

[2] A. Monguzzi , M. Frigoli , C. Larpent , R.Tubino and F. Meinardi, Adv. Funct. Mater. 2011, avaliable online. DOI: 10.1002/adfm.201101709.

8435-37, Session 7

Development and experimental validation of a predictive OLED model

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OLEDs are large-area light sources with potentially unique applications, e.g. as very thin light-emitting foils with every desired color. The light-emitting layer is only approximately 100 nm thick, and consists of a large number of organic semiconductor sub-layers, each with a different function. The physics which describes the opto-electronic processes is radically different from that in inorganic LEDs, due to the presence of strong disorder. Three-dimensional Monte-Carlo simulations show that the current density is therefore filamentary. In the talk, the full range of steps used to develop a predictive optoelectronic model is discussed, including supercomputer simulations and experimental validation using novel nanophotonic methods.

First, it is shown which progress has been made recently concerning the modelling of transport in an electrical field and across organic-organic organic interfaces. Subsequently, it is shown how the process of parameter extraction can be carried out efficiently, including making an assessment of the uncertainties and of their correlations, and it is shown how independent validation of the models used is possible by carrying out transient experiments (impedance and dark injection

measurements) in combination with modelling. Next, an application of three-dimensional modelling is shown for the case of a hybrid white multilayer OLED, i.e. with phosphorescent red and green emitting layers, and a blue fluorescent layer, and the results are compared to those of one-dimensional modelling. Furthermore, it is show how independent validation of the device model is possible by measuring the emission profile in multilayered OLEDs with nanometer scale resulution. A comparison between the predicted exciton generation profile and the measured emission profile provides information about the role of excitonic processes, such as energy transfer across organic-organic interfaces.

8435-38, Session 7

Non-isotropic emitter orientation and its implications for comprehensive efficiency analysis of organic light-emitting diodes

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The efficiency of organic light-emitting diodes (OLEDs) is limited since only a small fraction of the consumed electrical power is converted into light that is finally extracted to air. Most of the efficiency loss is caused by losses in radiative quantum efficiency (RQE) of the emitting guest-host system and by dissipating a huge part of the radiated energy to optical loss channels such as surface plasmons polaritons or waveguided modes, which cannot easily be extracted by common outcoupling structures. In order to increase the external quantum efficiency (EQE) of OLEDs new approaches need to be found. Recent studies show that the EQE can be enhanced considerably by horizontally oriented emitter systems [1], a feature that is well known for fluorescent emitters and has lately been demonstrated in phosphorescent state-of-the-art OLEDs [2,3]. By means of optical simulations we investigated the influence of non-isotropic emitter orientation on the effective RQE and on the outcoupling factor. We show that in order to achieve a consistent efficiency analysis it is indispensible to account for possible deviations from randomness. Ignoring these orientation effects leads to a significant misinterpretation of the RQE and other factors, which determine the external quantum efficiency of a device. Furthermore, we demonstrate the huge potential for efficiency enhancement of mainly parallel dipole emitter orientation in both fluorescent and phosphorescent OLEDs.

References:

[1] Jörg Frischeisen et al., Org. Electron. 12, 809-817 (2011)

[2] Michael Flämmich et al., Org. Electron. 12, 1663-1668 (2011).

[3] Tobias D. Schmidt et al., Appl. Phys. Lett. 99, 163302 (2011).

8435-40, Session 7

Experimental and theoretical study of the optical and electrical properties optimization of an OLED in a microcavity

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In the context of coherent organic light sources, we investigate experimentally and theoretically half-wavelength-thick Organic Light Emitting Diode (OLED) in a microcavity. The microcavity is based on a quarter-wavelength multilayer mirror on the one side and a thin aluminum semi-transparent layer on the other side. The microcavity center is filled with an Alq3/DCM2-based OLED heterostructure.

The challenge of this work with this basic structure is to optimize it from an optical and electrical point of view, hence to overcome two opposite effects. Indeed OLED with state of the art electrical efficiencies are thinner than a/2 optically-thick center of the microcavity, and any increase of the OLED heterostructure thickness to fulfill the microcavity needs results in a deterioration of the electrical properties.

The experimental study of the OLED thickness shows that a 620nm peak emission is obtained for a 123 nm-thick OLED heterostructure. The aluminum layer thickness is varied between 10 and 100nm and its impact on the current density and the quality factor is investigated. A trade-off between the quality factor and the current-density is obtained as a 20nm thick aluminum layer.

A directional emission at 620 nm and a linewidth narrowing are observed. The investigation of the emission from both the sides of the microcavity exhibits different spectra explained by the filtering properties of the cavity.

The simulations of the emission spectra is based on the transfer matrix method and takes into account the organic emitter position inside the cavity. The obtained results show the reduction of the quality factor with the aluminum layer thickness reduction, the different spectra from the top and bottom emissions and are in good agreement with the experimental results.

The study demonstrates the potential of the matrix transfer method with source inside the cavity to designing microcavity OLEDs towards organic laser diodes.

8435-41, Session 7

OLED light extraction improvement with surface nano-micro texturation based on speckle lithography

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Part of the light rays generated within a luminescent medium with a higher refractive index than that of the exit medium, typically air, undergo total internal reflection phenomenon (TIR); these rays will be trapped and guided into the emissive material and will not be extracted out of an OLED device for instance. Trapped light is reabsorbed and eventually converted into heat that will be detrimental to the device performance and lifetime. The amount of trapped energy is highly dependent on the values of the refractive indices involved in the multilayer stack constituting the light emitting device. The amount of trapped energy can be extensive and can even reach as much as 75% in certain cases. Solutions to improve the outcoupling efficiency are therefore attractive. In this paper we propose to use laser speckle to produce a random surface with controlled parameters to enhance the OLED outcoupling. A laser speckle pattern is transferred onto a photoresist which will be subsequently converted into a surface relief profile. The optical setup parameters drive the properties of such surface and thus the oucoupling properties. The resulting surface has a quasi-random shape which could be assimilated to a corrugated surface. We will show that these typical surfaces exhibit light extraction enhancement properties. The generated pattern is then transferred onto the exit interfaces of the emitting device. An extraction improvement close to a factor 3 is measured. The experimental approach is completed by a FDTD analysis. The use of a laser speckle shape is presented for the two OLED configurations: bottom and top-emitting. In both cases, substrate and/or cover optical interfaces are textured.

8435-62, Session 7

Scaling theory for percolative charge transport in disordered molecular semiconductors

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In the modeling of Organic Light-Emitting Diodes (OLEDs) it is essential to have a proper description of the charge transport in the organic molecular semiconductors used in these devices. This charge transport takes place by hopping between molecular sites, having random energies of which the density of states is often taken to be Gaussian. What is needed in the modeling is a simple and accurate mobility function that provides the dependence of the mobility on temperature, carrier density, and electric field. At vanishing electric field the hopping problem can be exactly mapped onto that of a random-resistor network of bonds between sites. In the zero-temperature limit the conductivity of this network is determined by the critical bond with the lowest conductance in the just percolating cluster of bonds with conductances higher than this conductance. However, at finite temperatures also bonds with conductances around this critical conductance should be included. We have recently developed a general scaling theory for including these bonds [1]. The essential parameter in this theory is a scaling exponent that depends on the specific hopping problem. We have determined this exponent for uncorrelated and correlated Gaussian disorder with Miller-Abrahams and Marcus hopping. For all four cases we obtain a simple expression for the mobility function that is very accurate in a broad range of temperatures and carrier densities. In addition, the theory sheds new light on the concept "transport energy", which has been central to many previous theories. In a next step, we will include the electric-field dependence.

[1] J. Cottaar, L.J.A. Koster, R. Coehoorn, and P.A. Bobbert, Phys. Rev. Lett. 107, 136601 (2011).

8435-42, Session 8

Charge transport and recombination in organic light-emitting diodes

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Charge transport is an important issue with regard to the understanding and optimization of electronic devices made from conjugated polymers. It has been demonstrated that the hole transport is governed by hopping between localized states, characterized by a mobility that depends on density, electric field and temperature. The transport of electrons is strongly reduced by traps that are Gaussianly distributed in energy in the band gap. Remarkably, the electron trap distribution is identical for all polymers considered.

The recombination processes in poly(p-phenylene vinylene) based polymer light-emitting diodes (PLEDs) are investigated. Photogenerated current measurements on PLED device structures reveal that next to the known Langevin recombination also trap-assisted recombination is an important recombination channel in PLEDs, which has not been considered until now. The dependence of the open-circuit voltage on light intensity enables us to determine the strength of this process. Numerical modeling of the current-voltage characteristics incorporating both Langevin and trap-assisted recombination yields a correct and consistent description of the PLED, without the traditional correction of the Langevin pre-factor. At low bias voltage the trap-assisted recombination rate is found to be dominant over the free carrier recombination rate.

8435-43, Session 8

Charge carrier dynamics in hybrid organic-inorganic light emitting devices

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Hybrid Light Emitting Devices (HyLEDs) have recently emerged as cheap and environmentally friendly alternatives for solid-state light emission. These novel structures comprise transition metal oxide charge carrier transporters combined with organic lumophores, which also participate in hole transport. The resulting samples are stable to air and oxygen moisture under operation without using encapsulating layers, thus, making these devices very interesting for technological applications. Moreover, they present competitive luminance and efficiency values compared to the well-known polymeric organic LED technology.

In this communication, we present our results regarding the research on the charge carrier dynamics in HyLEDs using transient electroluminescent techniques. Consequently, we can determine the influence of morphology and structural parameters into the device performance through electro-optical characterization. Since the emission of light can be tuned depending on the material's properties, we have worked on the inorganic charge transport layer through the preparation of 3D nanostructures that improve the quality of the interfacial organic-inorganic area, which reflects in the enhancement of the efficacy and luminance. On the other hand, we have studied the influence of the polymer properties on the performance of the HyLEDs. Moreover, we relate our findings with the stability of the devices.

8435-44, Session 8

Investigation of transfer mechanisms between two adjacent phosphorescent emission layers

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Organic light emitting diodes (OLEDs) have attracted increasing attention since they are promising candidates for highly-efficient solid state light sources. Reported key parameters, like efficiencies and lifetimes of such devices have steadily and rapidly improved over the last years. The peak efficiency, however, is often achieved at low current densities, and hence low brightness, due to exciton quenching by triplet-triplet annihilation and triplet-polaron quenching at high current levels [1].

It is therefore highly desirable to understand these limiting factors in more detail and develop strategies to avoid quenching effects which are applicable to white phosphorescent OLEDs. To this end, we have performed a systematic study on energy transfer and quenching mechanisms on two phosphorescent dyes in adjacent emission zones, namely red and green emission layers comprising Ir(MDQ)2(acac) and Ir(ppy)3 as emitters, respectively. We have investigated the performance by a variation of the emitter concentration and the emission layer thickness. By inserting different interlayer materials between the emission units we demonstrate that the triplet excitons are formed on the Ir(ppy)3 and subsequently transferred to the Ir(MDQ)2(acac) molecules via the hole transporting host material alpha-NPD of the red emission layer. The variation of the interlayer thickness shows that the triplet-transfer length is several tens of nanometers. The introduction of a mixed host approach for the red and green emission layer broadens the recombination zone, leading to balanced devices which do not change color with increasing current density. After the optimization an efficiency enhancement by 15% is achieved and the lifetime of the red-green emissive units can be more than doubled. Additionally, it is shown that this improved red-green emissive unit can be combined with a fluorescent blue emitter in a state-of-the-art stacked white emissive OLED.

References:

[1] M.A. Baldo, C. Adachi, and S. R. Forrest, Phys. Rev B 62, 10967, (2000).

8435-45, Session 8

Thermally activated delayed fluorescence in a spiro acridane molecule that enhances the EL efficiency in OLEDs

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Organic light emitting diodes (OLED), along with inorganic LEDs, owing to their advantages over current technologies in luminescent properties, manufacturing costs, power consumption and others, are predicted to dominate the field of general illumination in the near future. Today, display and illumination products comprising OLEDs based on phosphorescent emitters with 100% internal efficiency penetrate the market. Thermally activated delayed fluorescence (TADF) has recently got significant attention as the third mechanism of light production in OLEDs providing a promising efficiency as high as that of phosphorescent OLEDs, but with lower material costs.

A key factor to achieve efficient harvest of both singlet and triplet excitons for the light production in TADF systems is formation of a small energy gap between the lowest singlet (S1) and lowest triplet (T1) states of the molecule (∆EST). According to the Boltzmann statistics, reverse intersystem crossing (RISC) will be greatly enhanced at very low ∆EST due to the increasing probability of vibronic energy back-transfer between the T1 and S1 states. We designed and evaluated a spiro acridane-based molecule having a calculated ∆EST ~ 0.008 eV, and we show the TADF mechanism of this molecule. By employing a host material having higher T1 level compared to that of the TADF guest, we observed a surprisingly strong activation of the delayed fluorescence, which largely prevailes its fluorescence. By changing factors such as the doping concentration, the ambient temperature or presence of quenchers in the air, we can significantly alter the contribution from the TADF emission in solid state. The OLED devices based on our TADF emitter demonstrated higher external quantum efficiencies (EQE, ~9%) than the limitation of fluorescent OLEDs (5%), indicating the practical usability of TADF.

A key factor to achieve efficient harvest of both singlet and triplet excitons for the light production in TADF systems is formation of a small energy gap between the lowest singlet (S1) and lowest triplet (T1) states of the molecule (∆EST). Boltzmann statistics predict a rapid enhancement in reverse intersystem crossing (RISC) of triplet excitons to singlet level at RT when ∆EST < 0.1 eV. We have designed and evaluated a spiro acridane-based molecule having a calculated ∆EST = 0.007 eV and we show the TADF mechanism of this molecule. By employing different organic hosts for our TADF guest material we observe interesting relationship between the enhancement of photoluminescent properties of a thin film and the photophysical properties of host materials. For example, the weak light emission from a spiro-acridane emitter was enhanced about 7-fold and the decay time was raised from microsecond to millisecond order. We attribute these changes to the host material being an energy transfer channel for the TADF process. We also found that host materials with higher T1 level do not necessarily yield higher RISC. The OLED devices demonstrated higher EQE than the limitation of fluorescent OLEDs (~5%) indicating the practical usability of TADF.

8435-46, Session 8

Charge recombination and quenching mechanisms in organic field effect light-emitting transistors

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Organic light-emitting transistors (OLETs) are an emerging class of multifunctional devices, integrating the capability to generate light into a fully functional field-effect transistor. They attract increasing attention for providing both a novel device architecture for the investigation of fundamental optoelectronic properties and an innovative new approach for organic photonics. Possible applications include integrated nano-photonics for optical communications, flexible solid-state lightening, as well as the much-researched electrically driven organic laser. [1]

Currently, the fundamental processes of the OLET so that exciton formation and recombination are just partially understood. Indeed the well established insights gathered for OLEDs cannot simply be transferred to OLETs given the field-effect device architecture. Investigations on photophysics of the OLET, however, are rather scarce in literature and have concentrated on some specific aspects such as the width of the emission zone [2], [3]. Hence, a better insight into the mechanism governing light-generation and recombination efficiency is highly required for the realization of real opto-electronic devices based on OLETs.

Here we present a study on the excitonic-processes in single-layer OLETs, using fluorescence quenching microscopy. This technique allows to investigate the changes in exciton density between the on and off states of the device. It therefore enables us to measure the generation of excitons, as well as their quenching, in different regions of the transistors. Measurements on an unipolar devices show, that non-radiative exciton recombination in OLETs is dominated by Förster energy-transfer form excited neutral molecules to molecules ionized by free charges, localized at the immediate vicinity of the dielectric-semiconductor interface. We use this result to calculate the expansion of the charge layer, by measuring the quenching for semiconductor-layers of different thickness.

Moreover, measurements on ambipolar OLETs reveal the formation and movement of the recombination zone. 2D-mapping allows us to correlate this information with the observed electroluminescence, and so with the emission zone.

[1] Michele Muccini, Nature Materials 5, 605-613 (2006).

[2] Martijn Kemerink, Dimitri S H Charrier, Edsger C.P. Smits, Simon G.J. Mathijssen, Dago M. de Leeuw, and René a J Janssen, Applied Physics Letters 93, 033312 (2008).

[3] Jana Zaumseil, Chris Groves, Jessica M. Winfield, Neil C. Greenham, and Henning Sirringhaus, Advanced Functional Materials 18, 3630-3637 (2008).

8435-47, Session 8

Electroluminescence from organic nanocrystals

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For optoelectronic applications, organic semiconductors have several advantages over their inorganic counterparts such as facile synthesis, tunability via synthetic chemistry, and low temperature processing. Self-assembled, molecular crystalline nanostructures are of particular interest as they could form ultra-small light-emitters in future nanophotonic applications. For example, phenylene oligomers can form organic nanofibers upon epitaxial surface growth. The nanofibers emit polarized blue light when excited with UV light and can function as waveguides and random lasers. However, well-ordered nanofibers must be grown on mica substrates, which are not further processable. Here, we show a method to transfer such mica-grown nanofibers onto transistor platforms to facilitate a nanofiber-based light-emitting transistor [1]. The transfer is accomplished via a roll-printing method that maintains the intrinsic optical properties of the fragile, van der Waals-bonded molecular crystals. Transistor device configurations with either top or bottom contacts have been explored to optimize performance. Electrical characterization shows that the output characteristics of top contact devices are dominated by the nanofiber bulk due to low contact resistance resulting in space-charge limited transport. In contrast, bottom contact devices exhibit injection limited behavior due to larger energy barriers at the electrode-semiconductor interface [2]. Finally, we demonstrate clear blue electroluminescence from the fibers using a sinusoidal gate voltage [3], which results in sequential injection of hole and electrons from the same electrode with subsequent carrier recombination. This constitutes an important step in the sequence towards a nanoscale light-emitter with a desired color, which could be realized through synthesis of molecules with an appropriate luminescence spectrum. Ongoing studies are focusing on the integration of two types of nanofibers made from different molecules to realize a bi-color element.

[1] L. Tavares, J. Kjelstrup-Hansen, H.-G. Rubahn, Small, 7, 2460 (2011)

[2] L. Tavares, J. Kjelstrup-Hansen, K. Thilsing-Hansen, H.-G. Rubahn, Nanoscale Res. Lett. 6, 11 (2011)

[3] L. Tavares, J. Kjelstrup-Hansen, H.-G. Rubahn, Submitted

8435-48, Session 9

InGaN LED pumped polymer laser explosive sensor

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Conjugated polymers are attractive laser materials because of their high gain, broad spectra, tunability and simple fabrication. In addition they offer the prospect of adding functionality to inorganic semiconductors to make innovative hybrid optoelectronic devices. We recently demonstrated the world's first LED-pumped organic semiconductor laser (OSL), which gave green emission [1]. This approach opened the way for embedding organic lasers in composite devices that integrate inorganic diodes, OSLs and photodetectors on a single chip (EPSRC HYPIX project). Here we report work using a LUXEON Rebel LED (Philips Lumileds) to pump a highly-efficient light-emitting polymer, BBEHP-PPV, with a conventional distributed feedback (DFB) resonator. The InGaN LED is driven under nanosecond pulsed operation. We observe the onset of a sharp lasing peak at 537 nm for peak drive currents above 21 A/pulse, while the corresponding optical power density, from the LED chip, is 389 W/cm2.

Explosive sensing is a promising, emerging application for polymer lasers [2]. One exciting potential area of the application is to clear landmines left after military actions. As surface-emitting DFB lasers can be readily fabricated by soft lithographic means and as they can also be pumped using LEDs, there is the prospect for simple explosive sensors based on these materials. We demonstrate that an InGaN LED pumped BBEHP-PPV laser sensor can detect 10 parts-per-billion of the model explosive, 1,4-dinitrobenzene (DNB). After 90 s exposure of the polymer laser to DNB vapour, the lasing threshold increases from 32 A/pulse (535 W/cm2) to 50 A/pulse (771 W/cm2). For the same exposure time, the laser emission drops by 62% at a driving current of 61 A/pulse.

These sensitive inexpensive LED pumped OSL sensors could be used in humanitarian demining, complementing existing technologies such as ground-penetrating radar to improve the detection of hazardous objects.

8435-49, Session 9

Demonstration of broadly tunable laser emission and study of photodegradation issues in vertical external cavity surface-emitting organic lasers

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We demonstrate a Vertical External Cavity Surface-emitting Organic Laser (VECSOL), a VECSEL with an organic solid-state gain material, e.g. a dye-doped polymer thin film or an organic semiconductor. It gathers the properties of VECSELs (high conversion efficiency, excellent beam quality, power scaling capability, high versatility offered by the open cavity) with the key properties of organic thin films: low cost, ease of fabrication, broad emission spectra and wavelength tunability, easy chemical tuning, and high gain.

We built a simple structure consisting of a plane highly-reflective mirror onto which a thin film of dye-doped (Rhodamine 640 or Pyrromethene 597) PMMA layer was spun cast, and a concave output coupler closing the cavity. The pump source is a frequency-doubled Nd:YAG laser. We achieved a record conversion efficiency of 57% with a diffraction-limited output at 620 nm with Rhodamine 640. Tens of microjoules are typically obtained, and power-scalability up to 150 µJ is demonstrated together with a broad tuning range of 40 nm.

Dynamical numerical simulations, supported by experiments, revealed that the low "gain medium thickness over cavity length" ratio, combined to the short lifetime (~ns) of organics make the device efficiency much better with "long" pump pulses at a given pump intensity.

The high intracavity peak power together with the open cavity also allowed us to perform intracavity frequency doubling to demonstrate a deep-UV laser continuously tunable from 309 to 322 nm, with 2% efficiency, in a very compact setup (1-cm long).

Finally, photobleaching issues are discussed in detail through the influence of various parameters (pump pulse duration/intensity, manufacturing and storage conditions...) on the lifetime of operating VECSOLs for rhodamine 640 and pyrromethene 597. Half-lifetimes over 250 000 pulses are shown in P597 lasers in ambient conditions, without encapsulation.

8435-50, Session 9

High-power CW tunable solid state dye lasers: from the visible to UV

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We describe a high power CW solid-state dye laser setup. With perylene orange in PMMA as gain medium an output power up to 800 mW at 576 nm and a tuning range between 565 and 595 nm is reached. The laser output shows good long time power stability. The durability can be adjusted by variation of the pump power. A feedback loop controls the laser output. At a setpoint of e.g. 100 mW, the laser output can be provided for more than eight hours with a low noise level (RMS < 10%). The spectral width of the laser emission is less than 3 GHz and can be tuned over more than 30 nm. A circular mode-profile is achieved with M2 < 1.4 [1].

Via intra-cavity second harmonic generation 100 µW of 288 nm UV-radiation is achieved. As nonlinear element a 5 mm BBO (Beta-Barium Borate) crystal is used. The UV laser radiation can be tuned over 3 nm. The theoretical limit of UV output is estimated to 1 mW. To our knowledge we present the first tunable CW polymer UV laser.

While the output stability at the fundamental wavelength is reasonably good, in the UV region a significant enhancement of the noise level is observed. In addition the long time stability is reduced to few minutes. The limitation is mainly given by the photo-decomposition of the organic dye molecules. This process is analyzed via micro-spectroscopic studies.

[1] R. Bornemann, E. Thiel, P. Haring Bolívar, "High Power Solid-State CW Dye Laser", submitted to Optics Express, September 2011.

8435-51, Session 9

Whispering gallery modes microcavities with J-aggregates and plasmonic hot spots

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We have studied the optical properties of a hybrid system consisting of cyanine dye J-aggregates (both PIC and TDBC) attached to a spherical microcavity. Instead of the commonly accepted chemical bonding of dye molecules to the surface of microspheres or deposition of dye-doped sol-gel film, in our experiments microspheres were coated with J-aggregate shell utilizing the layer-by-layer assembly of the ultrathin films. In this approach we aimed to take advantage of light confinement in the Whispering Gallery Modes (WGMs) microcavity by placing the emitter (shell of J-aggregates) just at the rim of the microsphere, where the resonant electromagnetic field reaches its maximum. A periodic structure of narrow peaks was observed in the photoluminescence spectrum of the J-aggregates, arising from the coupling between the emission of J-aggregates and the WGMs of the microcavity. The most striking result of our study is the observation of polarization sensitive mode damping caused by re-absorption of J-aggregate emission. This effect manifests itself in dominating emission from the transverse magnetic modes in the spectral region of J-aggregates absorption band where the transverse electric (TE) modes are strongly suppressed. Strong suppression of TE modes reflects preferential tangential orientation of transition dipole moment of J-aggregates in deposited microcavity shell. Observed polarization sensitive mode damping observed in the spectral region of high J-aggregate absorption can be used for suppression of unwanted modes in high Q optical resonators.

We also demonstrate that the emission intensity can be further enhanced by depositing a hybrid layer of J-aggregates and Ag nanoparticles onto the spherical microcavity. Owing to the concerted action of WGMs and plasmonic hot spots in the Ag aggregates, we observe strongly enhanced Raman signal from the J-aggregates. Microcavities covered by J-aggregates and plasmonic nanoparticles could be thus useful for a variety of photonic applications in basic science and technology.

8435-52, Session 9

Evaluation of amplified spontaneous emission from photopumped thiophene/phenylene co-oligomers in polycrystalline states

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Thiophene/phenylene co-oligomers (TPCOs) have been attracting much interest as promising materials exhibiting excellent performance in electronic devices. Recently, single crystals of TPCOs have received much attention because of their optical stability and high-yield fluorescence. They showed amplified spontaneous emission (ASE) by high intensity pumping at room temperature and their laser oscillations were also demonstrated.

On the other hand, we have taken note of a polycrystalline state of TPCO and confirmed lasing phenomena for microdisk-microring disk oscillator that was made of polycrystalline TPCO. Therefore, potential performance of TPCO seems to be clear in not only a single crystal but also a polycrystalline state.

Here, we report the emission phenomena of planar waveguides consisting of polycrystalline TPCOs.

TPCOs used in this study were 2,5-bis(4-biphenylyl)thiophenene (BP1T) and 1,4-bis(5-phenylthiophen-2-yl)benzene (AC5). The planar waveguides of polycrystalline TPCOs were fabricated by vapor deposition onto SiO2 substrate, followed by thermal treatment over 240°C for 10 min, and rapid cooling. We overcoated a fluorinated polymer onto the thermal treated TPCO polycrystals. Fluorescence intensities of the samples were measured by pulse irradiation at a wavelength of 397 nm with ~200 fs pulse duration and 1 kHz repetition rate. An adjustable slit and a cylindrical lens were used to shape the beam into the stripe.

From the results of the evaluation for the emission intensity against an excitation energy density, the laser thresholds of BP1T and AC5 were found to be 55 and 120 μJ/cm2, respectively. We also confirmed spectral narrowing for both BP1T and AC5 above these threshold values. Dependence of the emission intensities on the excitation lengths was also performed: the cross sections (σ's) of amplification of BP1T and AC5 at the excitation energy density of about 200 μJ/cm2 were 7.8 x 10-16 and 0.7 x 10-16 cm2 respectively. BP1T was found to show the higher σ values than well-used laser dyes.

8435-53, Session 9

Study of two-dimensional photonic crystals cavity using organic gain materials

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The realization of electrically pumped organic laser diode remains a major challenge for organic optoelectronics[1]. In this work we aim at designing and realizing an optimal optical resonator for a low-threshold laser effect far below the device current-induced destruction i.e. <1kA/cm2. The threshold is characterized by a balance between two effects: the probability of spontaneous and stimulated emissions in a given mode of the microcavity that is inversely proportional to the mode volume, and the decay time of the field that is inversely proportional to the Q-factor [2]. Hence, the threshold is expected to scale as V/Q, that should be minimized. Among the various laser resonators, the concept of an OLED embedded in a photonic crystal microcavity represents a high quality factor laser configuration that exhibits a wavelength-scale modal volume [3]. That will allow the study of laser emission under electrical pumping at low threshold. In this work, we report an analysis of the operation of two-dimensional photonic crystal (2D PC) using organic gain materials. The 3D FDTD simulations of photonic crystal structure based on silicon nitride Si3N4 show that it is possible to achieve a quality factor of the resonator as high as Q=8900. The preliminary experimental results with 2D PC structures (with and without the active medium) are studied and analyzed by a far and a near field experimental setups. A good agreement between the calculated band structures and the experimental data is observed. The realized structure shows a very high band-gap that spans the emission spectrum of the used organic materials. The presented structure is a promising way to achieve laser emission with an extremely low threshold.

[1] E. J. W. List, C.-H. Kim, A. K. Naik, J. Shinar, and W. Graupner, Phys. Rev., 64, 155204 (2001)

[2] I. Protsenko, P. Domokos, V. Lefèvre-Seguin, J. Hare, J.-M. Raimond, and L. Davidovich, Phys. Rev. A 59, 1667-1682 (1999)

[3] Mikhail Boroditsky, “Modification of spontaneous emission in photonic crystals”, thesis, University of California (1999)

8436-02, Session 2

Subjective speckle perception tests evaluated with standardized speckle measurement method

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The introduction of lasers for projection applications is hampered by the emergence of speckle. In order to evaluate the speckle distorted image quality, it is important to devise an objective way to measure the amount of speckle. Mathematically, speckle can be described by its speckle contrast value C, which is given by the ration between the standard deviation of the intensity fluctuations and the mean intensity. Because the measured speckle contrast strongly depends on the parameters of the measurement setup, we propose in this paper a standardized procedure to measure the amount of speckle in laser based projection systems. To obtain such a procedure, the influence of relevant measurement set-up parameters is investigated. The resulting measurement procedure consists of a single digital image sensor in combination with a camera lens. The parameters of the camera lens are chosen such that the measured speckle contrast values correspond with the subjective speckle perception of a human observer, independent of the projector's speckle reduction mechanism(s). Furthermore, the speckle measurement procedure was performed with different cameras and the results were compared. Finally, a test group was subjected to a speckle perception test where the influence of the image content on the perception of speckle is discussed.

8436-03, Session 2

Comparison of the astronomical and multimedia image quality criteria

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This paper deals with the criteria definition of image quality in astronomy and their comparison with common multimedia approaches. Astronomical images have typical specific properties - high grayscale bit depth, size, high noise occurrence, sensitivity to point spread function deformation and special processing algorithms. They belong to the class of scientific images as well as medical or similar. Their processing and compression is quite different from the classical approach of multimedia image processing. The new compression algorithm ACC (Astronomical Context Coder) based on JPEG2000 standard and JPEG2000 are selected as a distortion source in this paper. Selected image quality criteria (multimedia and optimized for astronomical images) are tested on the set of images from the DEIMOS image database with miscellaneous level of the thermally generated CCD noise. The deformation of the point spread function (PSF) is also measured for both compression approaches.

8436-04, Session 2

Measuring image quality in overlapping areas of panoramic composed images

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Several professional photographic applications uses the merging of consecutive overlapping images in order to obtain bigger files by means of stitching techniques or extended field of view (FOV) for panoramic images. All of those applications share the fact that the final composed image is obtained by overlapping the neighbouring areas of consecutive individual images taken as a mosaic or a series of tiles over the scene, from the same point of view. Any individual image taken with a given lens can carry residual aberrations and several of them will affect more probably the borders of the image frame. Furthermore, the amount of distortion aberration present in the images of a given lens will be reversed in position for the two overlapping areas of a pair of consecutive takings. Finally, the different images used in composing the final one have corresponding overlapping areas taken with different perspective. From all the previously stated can be derived that the software employed must remap all the pixel information in order to resize and match image features in those overlapping areas, providing a final composed image with the desired perspective projection. The work presented analyse two panoramic format images taken with a pair of lenses and composed by means of a state of the art stitching software. Then, a series of images are taken to cover an FOV three times the original lens FOV, the images are merged by means of a software of common use in professional panoramic photography and the final image quality is evaluated through a series of targets positioned in strategic locations over the whole taking field of view. The targets used are the USAF1951 and the Slanted Edge; that allows measuring the resulting Resolution and Modulation Transfer Function (MTF). The targets are positioned at the centres and extremes of each individual image; those positions are used both to measure image quality performance before and after the final image composition and as features to be merged in the final image. As the merging software used allows for different methods to identify the points to be merged in the overlapping areas, the targets are the image contents used as a reference of the achieved merging performance. The work compares three situations: First panorama created from three wide angle images taken from a point of view very close to the object; second panorama created from three narrow angle images taken from a distant point of view; third image of the panoramic object taken in a unique image with a wide angle lens covering the FOV of the whole object, from a medium distance to the object. The results are compared in terms of success in features matching, image quality uniformity over the image field and final resolution of the different composed images.

8436-05, Session 2

Packet-header based no-reference quality metrics for H.264/AVC video transmission

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Video quality assessment is an essential tool in the planning, design and monitoring of video distribution systems, especially those that use best-effort IP networks, i.e. networks with no guarantee of delivery. Since audiovisual applications have strict requirements in terms of bandwidth, delay, jitter and packet loss rate, it is essential to monitor video quality in many network nodes to identify possible constraints and problems.

In this paper, a low complexity quality assessment technique for H.264/AVC coded video is proposed to satisfy requirements of video quality monitoring inside the network, and not at the decoder side as previous state-of-the-art. Thus, the methods proposed can only extract information that is available in the video distribution protocol stack (such as packet loss rate) and from the bitstream headers (such as the network adaption level header) that encapsulates the video compressed data. With the extracted characteristics, the correlation between the source and the decoded video is estimated with a piecewise linear model for easy deployment in many network nodes.

To perform the validation and benchmarking of the no-reference packet-header video quality assessment (VQA) system, it is important to use

subjective evaluation results that are well correlated with the human perception of video quality. Thus, a public available subjective evaluation database was used to provide the necessary subjective mean opinion scores (MOS) for H.264/AVC compressed video when subjected to packet losses. The experiments performed in this paper attempt to define two critical aspects of the proposed system:

Feature selection: Definition of the best features that should be used by the packet-header piecewise linear model. The following experiments were performed with some of the features proposed in Section III: i) LD - amount of lost data; ii) BST - packet burst. In these experiments only one feature was used by setting the piecewise linear model parameter n=1. Then, two features were combined (n=2) to improve estimation accuracy: iii) BST+PLR - burst and packet loss rate; iv) SLR_P+SLR_B - slice loss rate for P and B slices; v) SLR_IP+SLR_B: slice loss rate for I/P slices and B slices. Regarding case iv), only the SLR of P and B frames was considered since it was observed that SLR_P and SLR_B are better correlated to MOS values when compared to SLR_I. Then, in case v), SLR_IP represents the slice loss rate for I and P slices and SLR_B the slice loss rate for B slices. After performing several experiments where each combination of slice loss rates for different slice types was tested, this specific mix of slice types had the best performance. Note that the linear regression dimensionality (n=2) is low which helps to lower the VQA complexity.

Performance assessment: After establishing the best mix of features the performance can be evaluated in comparison to other low complexity metrics such as PLR with one linear region, often used in many video quality monitoring applications.

8436-06, Session 3

A survey on HDR visualization on mobile devices

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There is a vast body of literature concerning the capture, storing, transmission and display of High Dynamic Range (HDR) imaging. Nevertheless there are few works that try to address the problem of getting HDR on mobile devices. Their hardware limitations, such as processing power, storage space, graphics capabilities and screen characteristics, transform that problem in a big challenge. One can argue that given the very small screen size of the mobile devices it is not worthy to think on visualize HDR content on mobile devices. However, since more and more HDR content is being produced (nowadays HDR photography is very popular) and given that in a few years it can become a standard, it is necessary to provide the means to visualize HDR images and video on mobile devices. The main goal of this paper is to present a survey on HDR visualization approaches and techniques developed specifically for mobile devices. This survey will cover both HDR static images and video visualization. To understand which are the main challenges that need to be addressed in order to visualize HDR on mobile devices, an overview of their main characteristics is given. This will allow identifying mobile devices limitations and providing some clues on how to overcome them. The very low dynamic range of most of mobile devices' displays implies that a tone mapping operator (TMO) must be applied in order to visualize the HDR content. The current status of the research on TMO will be presented and analysed, a special attention will be given to the ones that were developed taking in account the limited characteristics of the mobile devices' displays. Another important issue is visualization quality assessment: to what extent one can visualize HDR content in mobile devices without losing the main characteristics of the original HDR content. Thus, evaluation studies of HDR content visualization on mobile devices will be presented and their results analysed.

8436-07, Session 3

Perceptual colour spaces for high dynamic range image compression

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This paper presents a two layer CODEC architecture for high dynamic range image compression. The first layer contains the tone mapped image obtained using a conventional low dynamic range encoding approach, such as JPEG. The second layer contains the image difference, in perceptually uniform colour space, between the result of inverse tone mapped low dynamic range content and the original image. We present techniques for efficient implementation and encoding of non-uniform tone mapping operators. Different colorspaces and compression algorithms are compared.

In a general approach to the distribution of HDR content, the tone mapped result is stored as the LDR layer and a downsampled HDR image is stored as enhancement layer. No restrictions are imposed on compression and tone mapping algorithms. When HDR image is upsampled the higher frequencies are taken from LDR image. For local tone mapping operators the technique for restoring impulse response function is introduced. One of the disadvantages of the above popular approach is the increased complexity of the decoder. Not only has it to decompress both streams, but in case of a local tone mapping operator, complex calculations are required to restore the impulse response function. Global tone mapping operators are easier to handle, but they have worse performance.

Local tone mapping operators model the adaptivity of the human eye. Literature suggests that the radius of spatial adaptation corresponds to 1/4 to 1/2 of image size. In that case the calculation of local inverse tone mapping function can be done on a very coarse grid (10x10 to 20x20 gave good results during experiments). Each function can be represented as piecewise-linear function with limited amount of nodes. This approach enables to shift the calculation burden towards the encoder and enables very efficient GPU acceleration of this operation - just one 3D texture lookup per pixel.

The calculation of the inverse tone mapping table can be performed by either sorting the pixel intensities in the pixel neighbourhood as proposed in or by using weighted least squares fitting where the weights used decreases with the distance from the node position. The least squares method requires just one pass over the image to accumulate the necessary sums. It can be accelerated using GPU hardware (for example, for GPU-assisted histogram collection)

The inverse tone mapping allows predicting of HDR content from LDR images with higher accuracy and enables to store the difference information as the HDR layer. When the LDR content is no longer required the HDR image can just omit LDR layer and inverse tone mapping table and transmit HDR data as single layer.

Compact representation of tone mapping operator can have other advantages: first of all, the typical usage of HDR image assumes tone mapping to device with dynamic range, in between LDR in HDR content. The table can greatly accelerate the tone mapping algorithm. For some applications there will be no need for decoding HDR layer at all. Secondly when HDR only content is distributed, the relatively small tone mapping table will allow speeding up the image adaptation for the particular device.

8436-08, Session 3

Full high-dynamic range images for dynamic scenes

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The limited dynamic range of digital images can be extended by

composing photographs of the same scene taken from the same camera at the same view point at different exposure times. This is a standard procedure for static scenes but a challenging task for dynamic ones. Several methods have been presented but few recover high dynamic range within moving areas. We present a method to recover full high dynamic range (HDR) images of dynamic scenes, even in moving regions. Our method has 3 steps. Firstly, areas affected by motion are detected to generate a “ghost mask”. Secondly, we register dynamic objects over a reference image (one of the input image sequence). Thirdly, we combine the registered input photographs to recover HDR values in a whole image using a weighted average function. Once matching is found, the assembling step guarantees that all aligned pixels will contribute to the final result, including dynamic content.

Four different motion detection approaches were used: variance-based, median threshold bitmap (MTB), pixel relation method (PRM), and intensity mapping function (IMF). Image registration is calculated on motion clusters computed from the ghost masks, with an iterative process on an image pyramid, to find successive translation and rotation transformations. Similarities that guide the registration process are computed on four different manners: the sum of squared differences, normalized cross correlation (NCC), mutual information (MI), median bitmap difference (MBD).

Tests were made on more than 20 sets of sequences, with moving cars or pedestrians and different background. Our results show that IMF detects best motion regions while NCC finds the most accurately similarities between images. Non rigid movement is allowed up to a point the size chosen for the motion clusters. The final composition is an HDR image with no ghosting effect and all dynamic content present in HDR values.

8436-09, Session 3

High-dynamic range video acquisition with a multi-view camera

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We propose a new HDR video camera with 8 views used for the content acquisition for auto-stereoscopic displays. To compensate for the limitation of each sensor’s captured intensity range, our methodology builds on a solution combining images taken from different exposures. Instead of varying the exposure for each view, we’ve fixed the exposure variation by applying different neutral density filters on each objective. In practice, we use 3 pairs of 0.3, 0.6 and 0.9 filters, plus two views without filters, which are positioned to minimize the intensity difference between two neighbor images. The advantage of such approach is twofold. First, for each video frame several exposures are known. Second, by using filters, we do not need to worry about synchronization issues since each frame takes the same time to be captured by the 8 cameras. For each pixel of each view, an HDR value is computed by a weighted average function applied to the values of matching pixels from the other views. The difficulty of building the pixel match list is simplified by the property of our camera which has 8 aligned, equally distributed objectives, calibrated in their position and color characterization. For each video frame, a factor based on the percentage of light reaching to the sensor is applied to the 8 images so that color intensities are similar on all images. The list of matches is therefore calculated by looking for pixels of similar colors in a known area. At each frame, this results in an individual HDR image for each view while only one exposition per view was taken, that can be tone-mapped for auto-stereoscopic display. Our results are promising and show high similarity when compared to reference HDR images reconstructed from a set of images with exposition variation on each singular objective.

8436-10, Session 3

Speed up of optimization-based approach to local backlight dimming of HDR displays

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Local backlight dimming in Liquid Crystal Displays (LCD) is a technique that allows reducing power consumption and simultaneously increasing the contrast ratio to provide a High Dynamic Range (HDR) image reproduction. Several backlight dimming algorithms exist with focus on reducing power consumption, while other algorithms aim to enhance contrast, with power savings as a side-effect. One such algorithm [1] models backlight dimming as a linear programming problem to find the optimal solution. The target is to minimize the difference between an ideal output and the actual output, where the variables are the intensities of the backlight segments and the transmittance of the Liquid Crystal (LC) pixels. Its intention is to enhance contrast while keeping artifacts as light leakage and clipping (pixels receiving an insufficient amount of backlight) to a minimum.

This work proposes a fast version of the above mentioned algorithm. It aims to speed up execution by decreasing the number of variables concerned when calculating the solution. This is done by using just a subset of the input pixels. These pixels are selected among those showing leakage or clipping when a backlight dimming algorithm is applied. The optimization problem is then solved with this reduced set, that can be used to iteratively calculate more accurate solutions. The algorithm has been further developed to be applied on a local backlight dimming enabled HDR display with 2202 controllable backlight segments taking perceptual aspects into account. The quality of the results has been assessed against other dimming methods using objective quality models. Good models of both the display system and human perception are critical for creating and assessing a perceptually high quality HDR image display. Using a pixel subset to solve the full optimization problem can reduce complexity in other local backlight dimming approaches, too.

8436-11, Session 4

Image analysis in modern ophthalmology: from acquisition to computer assisted diagnosis and telemedicine

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Medical digital imaging has become a key element of modern health care procedures. It provides visual documentation and a permanent record for the patients, and most importantly the ability to extract information about many diseases. Modern ophthalmology thrives and develops on the advances in digital imaging and computing power. In this work we present an overview of recent image processing techniques proposed by the authors in the application area of digital eye fundus photography. Our applications range from robust auto-focusing in the near infrared imaging system embedded in a retinal camera to image restoration via blind deconvolution and visualization of structural changes in time between patient visits. All proposed within a framework for improving and assisting the medical practice and the forthcoming scenario of the information chain in telemedicine.

8436-12, Session 4

Evaluating the effectiveness of treatment of corneal ulcers via computer based automatic image analysis

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Corneal Ulcers are a very common eye disease that requires prompt treatment. Recently a number of treatment approaches have been introduced that have been proven to be very effective. Unfortunately, the monitoring process of the treatment procedure remains manual (i.e. measuring the width and the height of a corneal ulcer from an image and calculating an estimated area of the ulcer and comparing to that of the area of the cornea, approximated from the same image) and hence is time consuming and is prone to human errors. In this research we propose an automatic image analysis based approach to measure the size or an ulcer and its subsequent further investigation to determine the effectiveness of any treatment process adopted.

In Ophthalmology an ulcer area is detected for further inspection via luminous excitation of a dye. Usually in the imaging systems utilised for this purpose (i.e. a slit lamp with an appropriate dye) the ulcer area is excited to be luminous green in colour as compared to rest of the cornea which appears blue/brown. In the proposed approach we analyse the image in the HVS colour space to first segment green areas. Initially a pre-processing stage that carries out localised histogram equalisation is used to bring back detail and colour in any over or under exposed areas. Subsequently using a 'rule based approach' we remove erroneous regions of interest from the detected 'green' areas. Secondly we deal with potential reflections from the affected areas by making use of affine image transformations to remove image highlights. It is noted that highlighted over exposed segments of the ulcer areas will not be detected as 'green' and hence will erroneously contribute towards ulcer area measurement if not otherwise identified. Thirdly the corneal boundary is detected by registering an ellipse to the corneal boundary detected via edge detection. This removes the impact of breakages of the corneal boundary due to occlusion and noise. The ratio between the ulcer area, confined within the corneal area to the corneal area is used as a measure of comparison. Utilising the above ratio as a measure removes the need for registering corneal boundaries between temporal measurements of the same patient.

We present a fully implemented computer based tool to measure and monitor the progress of the healing process of a corneal ulcer. When presented with ulcer measurements over a period of time the tool draws a graph indicating the reduction of ulcer area relative to the fixed sized area of the cornea. The paper will also provide additional details of the hardware integration of the optical system comprising of the slit lamp, digital camera, optical couplers and flasher. We will present results of three clinical case studies. Further the paper will provide an insight into computer vision algorithms that can be used to further evaluate the healing process of an ulcer, such as algorithms to determine ulcer colour, texture and contour/shape.

Corneal Ulcers, localised histogram equalisation, image transformations

8436-13, Session 4

A comprehensive study of texture analysis based on local binary patterns

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Image classification is still a challenging topic in computer vision due to the multiplicity of elements involved. The key for the success not only depends on a robust classifier but also relies in a good selection of the feature descriptors. Texture is the term used for characterizing the surface of an object and constitutes a salient perceptual cue for object identification and recognition of an image. Since Ojala et al proposed a modification of the original Wang's algorithm, the local binary pattern (LBP) techniques have gained increased importance due to its computational simplicity and more importantly for encoding a powerful signature for describing textures. The classical LBP approach uses a 3x3 square mask called ``texture spectrum'' which represents the neighborhood around a central pixel. Typically, the intensity values of the pixels in the square mask of analysis are thresholded by the value of the central pixel and multiplied by a weighting function according with their pixel positions. However, Ojala's algorithm presents some limitations such as its noise sensitivity and its lack of invariance to rotational changes. This has fostered many extensions of the original LBP approach that in many cases are based on minor changes in order to attain e.g. illumination and rotation invariance and improving the noise robustness. In this paper we perform a comparative study of the Ojala's LBP proposal with other LBP approaches and extensions recently proposed in the literature. In particular we undergo a texture classification study using two different test databases: Brodatz and CUReT and under different scenarios such as rotation and illumination changes or noise degradation and for different sizes of LBP masks. Other LBP extensions have been evaluated using different neighborhood and thresholding criteria. LBP histograms have been evaluated using two metrics frequently used in the literature: Kullback-Leibler and ordinal distance. This study will be a valuable insight for establishing a robust and efficient texture descriptor for solving real world problems.

8436-14, Session 4

Fast texture evaluation of textiles using the GLBP technique in GPU architecture

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Manufacturers conduct visual inspection processes to certify the quality of their products. Commonly, these tasks are performed by human experts, relying in subjectivity. Objectivity, accuracy and repeatability can be achieved by using computer vision extracting visual features from the products. Accurate inspection demands high discriminant, symmetric invariant, statistically independent, noise resistant and reliable features. Moreover, high levels of production require features computed with real/short time algorithms.

Local Binary Pattern (LBP) techniques have succeeded for fast automation of image analysis, with a major advantage in robustness against illumination conditions. LBP techniques assign one number (LBP-number), representing local intensity variations to each pixel in an image, which are calculated from Boolean comparisons of intensity values around the pixel with intensity values of the pixels. Arrangement of Boolean results determines the LBP-numbers. Symmetric versions of local intensity variations can be labeled with the same LBP-number using look up tables while evaluating circular neighborhoods. Intensity values of points on the circle are computed using interpolation. Although the majority major research is conducted for evaluating texture, described by frequencies of LBP-numbers on the images, other image features such as color and shape can be also described.

A recent variation of the LBP techniques, named Geometric Local Binary Pattern GLBP technique, showed an increasing in the performance for detecting small changes of local texture. The algorithm was tested for evaluating global deviations of texture due to degradation in carpets. It assigns a set of numbers resulting from evaluating oriented neighborhoods from the pixel instead of assigning one number from evaluating a circular neighborhood around the pixel. An oriented neighborhood is composed of points located on a set of circular neighborhoods with different radii, considering adjacent points with only one point per circle. Boolean comparisons are performed between adjacent points. Combining oriented neighborhoods defines geometric structures.

The speed of both, LBP and GLBP, algorithms is determined by the interpolation of the intensity values on the circles together with the Boolean comparisons. Fast computation of these operations can be achieved using multiprocessing architectures such as FPGA (Field-Programmable Gate Array) and GPU (Graphic Processing Unit). Both architectures have high capacity for single parallel algebra operations. Particularly, GPU technology was limited for many years to accelerate graphics processes but nowadays it offers accessible programing tools. GPUs are cheaper compared to FPGAs. This poses GPUs better for developing low cost inspection systems.

We implement LBP and GLBP techniques in an NVIDIA GeForce GT 525M using CUDA language. Images are manipulated using OpenGL. LBP and GLBP techniques are compared in CPU and GPU environments in terms of speed and accuracy. Algorithms are tested for detecting defects in fabrics as well as for evaluating global deviations of texture in carpets.

Results show than reliable and real time automated visual inspection can be developed, with GLBP technique showing higher distinction when evaluating similar textures. In further research we want to explore the potential of the GLBP look up tables to incorporate other features i.e. colors, shapes or edges, to identify objects in real time.

8436-15, Session 5

New high-speed CMOS image sensor including linear and non-linear functions in the focal plane

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Nowadays camera-on-a-chip image sensors are more and more necessary in many facets of human activity for example in mobile phones, video surveillance systems, embedded medical imaging and industrial vision systems.

For this, image sensors require the integration in the focal plane (or near the focal plane) of complex image processing algorithms. Such devices must meet the constraints related to the quality of acquired images, speed and performance of embedded processing, as well as low power consumption. To achieve these objectives, low-level analog processing allows to extract directly the useful information in the scene. For example, edge detection step followed with a local maxima extraction allows to facilitate the high-level processing like objects pattern recognition in a visual scene.

In this context, our goal was to design an intelligent image sensor prototype and to achieve a triple function: high speed image acquisition, linear image processing (like edge detection filters) and non-linear image processing (like local minima and maxima calculations).

For this purpose, we present in this article the design and test of a 64x64 pixels CMOS image sensor built in a standard CMOS Technology 0.35µm and including linear and non-linear image processing.

The architecture of our sensor is based on the implementation, for each pixel, of an analog process unit (APU). This APU calculates, in real time, in a 2x2 pixels neighborhood, the convolution function (linear function) and also the minimum and maximum values (non-linear functions).

Each APU needs 40 transistors and the pitch of one pixel is 40µm. The total area of the 64x64 pixels is 11mm2.

Our tests have shown the validity of the main functions of our new image sensor like fast image acquisition (1K frames per second), convolution and minima/maxima calculations in less then one ms.

8436-16, Session 5

Precise and effective fixed-pattern correction for logarithmic high dynamic range CMOS image sensors achieving low-noise equivalent contrast over illumination

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Logarithmic High Dynamic Range CMOS (HDRC) image sensors exhibit the highest Dynamic Range and a straight forward image acquisition compared to other High Dynamic Range imagers or techniques. The nearly constant pixel random noise over the illumination range, in contrast to sensors with linear or piece-wise linear Opto-Electronic Conversion Function (OECF), gives rise to a balanced contrast resolution.

In the paper the Noise Equivalent Contrast (NEC) will be introduced as a figure of merit to compare both imager types with non-linear and linear OECF, which leads to the incremental Signal-to-Noise Ratio (iSNR) and SNR, respectively. This will be shown by measurements of OECF and NEC performed with our logarithmic HDRC imager. The resulting iSNR, related to ISO15739, will be quantitatively compared to SNR data of a linear imager according to EMVA1288 standard.

The benefits of the logarithmic imager come with the necessity to correct CMOS technology dependent pixel to pixel variations, namely the MOS transistor threshold and gain variations and the photodiode dark current distribution contributing to an overlaid Fixed-Pattern in the raw image data. Depending on the required quality and the allowed computational complexity a Fixed-Pattern Correction (FPC) algorithm should correct from the most dominant up to all three non-uniformity parameters per pixel in the digital signal chain of a camera.

In the paper the NEC methodology will be extended with the spatial pixel to pixel variations. In this part a newly developed digital FPC algorithm for logarithmic HDRC imagers will be described. The advantage of the precise correction of all three non-uniformity parameters and the effective mathematical computation avoiding floating point arithmetic makes it ideal for real-time hardware implementation on an embedded video system. Again iSNR data of measurements and simulations with the new FPC algorithm will be discussed.

8436-17, Session 5

A new approach for system level active vision sensor

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Today's digital pictures are obtained from image sensors that are used as passive photon integrators. Moreover, grabbed pictures require image processing that is essentially done by external digital processors. This makes a clear separation between the image sensing part, and the associated computing part which is dedicated to image processing. However, the embedded systems constraints limit the processing capacity of such designs and usable image processing algorithms. This traditional approach restricts the actions that can be done on sensors. Embedded image processing grows considerably with the arrival of low cost sensors. The processing part has to deal with already grabbed pictures, even if the exposure parameters were wrong. Conversely, a sensor that is able to modify its parameters during the exposure in order to avoid later computation would be a benefit. The proposed approach is based on a fast self-adaptable preprocessing architecture of the image sensor. This approach is based on fast feed-back on the sensing level by a digital preprocessing. Moreover, global system-level feed-backs and control is implemented leading to merge the different parts of the sensor. The use of communications between the sensing and processing parts is necessary to permit these feedbacks, leading to new types of designs. 3D stacking integration technology is pertinent for such sensor architecture, thus making full sensor as an image acquisition stack. Indeed, it gives a parallel access to the sensing part of the sensor making possible feed-back on separated group of pixel. Consequently, the pixel level is separated in several macro blocs that are separately controlled. They are associated with analog-digital converters delivering image blocs to the preprocessing level. Exposure time and conversion gain are controllable on each on these blocs in order to permit a direct control during the acquisition. The preprocessing level is also separated in several preprocessing elements which are devoted to the fast computation of a pixels macro-bloc. Their goal is to compute the associated pixels bloc during the picture exposure with operation such as adaptive filters, in order to permit accurate feedbacks on the sensing parts. This approach is a totally new way of designing a full active system level sensor. The presented work is first validated by porting the application of complete movement detection in contrasted scene. This portage is done on a VHDL model of the sensor allowing validation of near pixel feedback in order to produce HDR images, then, they are computed by preprocessing elements to extract movement features. This work presents a new way of designing a full active image sensor at system level and opens new approaches for computer vision algorithms. These algorithms benefits on feedback possibilities and preprocessing adaptation. Moreover, its genericity permits a wide range of possible applications for such an image sensor, such as security or military applications, but also scientific applications or image stabilization.

8436-18, Session 5

Multi target tracking implementation in the high data throughput ebCMOS camera system: LUSIPHER prototype

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The domain of the low light imaging systems progresses very fast, thanks to new detection technologies, such as the emCCD (electron multypling CCD) or the ebCMOS (electron bombarded CMOS).

A proof of the concept of Multiple Target Tracking (MTT) at the ultimate limit of low light imaging, the Single-Photon Imaging (SPI), has been presented at SPIE IS&T/2011 with an data analysis performed off-line.

First of all, we present the ebCMOS camera system (10 Gb/s) that is able to track every 2 ms more than 2000 targets with few photons received continuously from each point source. The point light sources (targets) can be fluorescent beads, e.g., CdSe Quantum Dots, SiC, fluo-nano diamonds, single molecules or spots generated by a microlens array (Shack-Hartmann) for adaptive optics.

Then, the MTT algorithm is explained in detail within three steps: (i) photon impact maps reconstruction (ii) target list update and (iii) target list validation and visualisation bank.

The implementation on a rugged workstation is also discussed. A special care (SSE4 instructions) has been devoted to reduce the computing time in order to sustain continuously the high frame rate.

For the first time, the MTT algorithm has been tested in-line with more than 2000 spots generated by a Shack-Hartmann microlens array in the field of view of the ebCMOS camera system. The results and the performances of the system on the identification and tracking are presented and discussed. The wave front is reconstructed in-line at a 500 Hz frame rate.

To conclude, we discuss the feasibility of the SPI-MTT with a megapixel ebCMOS camera system and a 1 kHz frame rate through a 40 Gbit/s ethernet link between the acquisition system and the workstation.

8436-19, Session 5

Composed filter for attenuating bi-frequential noise on LCD-generated ronchigrams

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This work aims to design a filter in order to attenuate high- and medium-frequency noise in optical test images (ronchigrams) without changing the edges and original characteristics of the test image, generated by traditional filters (spatial or frequential). The noise produced by the LCD pixels (used as a diffraction grating in the Ronchi test) was analyzed. That diffraction is modulated by the spherical wavefront of the mirror under test, generating at least two frequency band noise levels in the ronchigram image. To reduce this bi-frequential noise, we propose to use an array of filters with the following structure: a low-pass frequential filter LPFF, a band-pass frequential filter BPFF and a circular mask spatial filter CMSF; thus obtaining the composed filter CF=LPFF-(BPFF)(CMSF). As results we show several sizes of filters were used to compare their signal-to- noise ratio against simple filters (low- pass and band- stop).

8436-20, Session 6

Visual attention: low-level and high-level viewpoints

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Computer models of visual attention aim to imitate aspects of the behaviour of the human visual system. The models identify image regions that attract our attention either directly by our gaze or covertly in our peripheral vision. The models of Itti and Tsotsos all rely upon feature measurements to calculate levels of attention assigned to pixels in the image. Typically they reflect the operation of low level centre-surround mechanisms that involve no longer term memory of previous experience. At higher levels, attention is driven by memory of earlier attentional experiences. In this sense processes of attention cannot be truly separated from recognition mechanisms where attention is also dependent on the strength of similarity with attentional data gathered earlier. There is therefore an overall process in which world data is collected and filtered by attentional processes, but at the same time is matched with stored data that can reinforce the current level of attention.

This paper outlines the principal models of visual attention and explores an approach that uses low level attentional data to identify higher level structure. The relationships between pairs of interest points are compared between images and the largest sets of points which match and bear the same relationships to each other in both images form maximal cliques. The size of the maximal clique determines the level of similarity [1] and hence the level of attention arising from memory. The approach avoids the use of pre-selected features and the need for training sets of data. It also allows a trade off of measurement precision of input data for the associative power of large cliques of interest points. Experiments have shown that the framework fails in the same manner as the human visual system when applied to images from the Poggendorff illusion [2].

[1] F W M Stentiford and A Bamidele, “Image recognition using maximal cliques of interest points,” Int. Conf. on Image Processing, Sept. 26 - 29, Hong Kong, 2010.

[2] F W M Stentiford, “Interest point analysis as a model for the Poggendorff illusion,” Human Vision and Electronic Imaging XVII, SPIE Conf., San Francisco, 23 - 26 Jan., 2012.

8436-21, Session 6

Motion statistics at the saccade landing point: attentional capture by spatiotemporal features in a gaze-contingent reference

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Motion is known to play a fundamental role in attentional capture, still it is not always included in computational models of visual attention. A wealth of literature in the past years has investigated natural image statistics at the centre of gaze to assess static low-level features accounting for fixation capture on images. A motion counterpart describing which features trigger saccades on dynamic scenes has been less looked into, whereas it would provide significant insight on the visuomotor behaviour when attending to events instead of less realistic still images. Such knowledge would be paramount to devise active vision systems that can spot interesting or malicious activities and disregard less relevant patterns.

In this paper, we present an analysis of video segmentation and spatiotemporal features as observed at the next saccade landing point to extract possible regularities in the fixation distribution to contrast with non-fixated points feature distribution. A substantial novelty in the methodology is the evaluation of the features in a gaze-contingent frame of reference. Each video sequence fragment is indeed stabilized with respect to the current fixation, accounting for fixational eye movements., as it is the case when a subject keeps the objects of interest in the fovea.

This allows us to estimate covertly selected motion cues in a retinotopic fashion.

We consider video sequences and eye-tracking data from a recent state-of-the art dataset and test a motion saliency measure againts human performance. Obtained results can be used to further tune saliency computational models and to learn to predict human fixations on video sequences or generate meaningful shifts of active sensors in real world scenarios.

8436-22, Session 6

Data-driven approach to change- and motion-based visual attention modelling

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Recent years have witnessed increased interest within the scientific community when it comes to attention and saliency in videos. While video can be treated as a sequence of frames and bottom-up saliency and attention are a well researched problem, full-fledged biologically inspired computational models of attention are too computationally intensive for real world applications such as video skimming and video quality assessment. Also such models do not take into account motion and luminosity changes (such as due to flickering lights).

Recently, Culibrk et al. [1] proposed a motion- and change based visual saliency model, which can be computed efficiently and applied it to enhance video quality assessment. The approach is based on multiscale background subtraction and change detection. Outlier detection is then used to detect salient motion and changes within the frames of the video. The approach achieves meaningful results and models important aspects of the human visual system.

In this paper we aim to enhance the model proposed by Culibrk et al. by incorporating knowledge gained from human subjects' eye-tracking experiments. We propose to use the basic multiscale change and motion related features of the model, but to replace the crude outlier detection with models learned from experimental data.

To do so we propose the use of machine learning algorithms. The ground truth data used to train the machine learning algorithms is the data that has been collected for 18 different viewers and 24 videos containing some well know automated surveillance and crowd scenes.

Diverse machine learning (neural networks, decision trees, AdaBoost, random forest) will be evaluated as estimators of the visual saliency and results of this evaluation presented in the paper.

In addition, we will explore the possibility of identifying the precise features most relevant to user attention allocation via automated feature selection approaches typically used in data mining.

[1] ulibrk, D.; Mirkovi , M.; Zlokolica, V.; Pokri , M.; Crnojevi , V.; Kukolj, D., "Salient Motion Features for Video Quality Assessment", Image Processing, IEEE Transactions on, April 2011, Vol. 20, Issue 4, pp: 948 - 958.

8436-23, Session 6

Real-time computational attention model for dynamic scenes

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Providing real time analysis of the huge amount of data generated by computer vision algorithms in interactive applications is still an open problem. It promises great advances across a wide variety of fields.

When using dynamics scene analysis algorithms for computer vision, a trade-off must be found between the quality of the results expected, and the amount of computer resources allocated for each task. It is usually a design time decision, implemented through the choice of pre-defined algorithms and parameters. However, this way of doing limits the generality of the system. Using an adaptive vision system provides a more flexible solution as its analysis strategy can be changed according to the new information available. As a consequence, such a system requires some kind of guiding mechanism to explore the scene faster and more efficiently.

We propose a visual attention system that it adapts its processing according to the interest (or salience) of each element of the dynamic scene.

Somewhere in between hierarchical salience based and competitive distributed, we propose a hierarchical yet competitive and non salience based model. Our original approach allows the generation of attentional focus points without the need of neither saliency map or explicit inhibition of return mechanism. This new real-time computational model is based on a preys / predators system. The use of this kind of dynamical system is justified by an adjustable trade-off between nondeterministic attentional behavior and properties of stability, reproducibility and reactiveness.

8436-24, Session 7

Use of subpixel techniques in pocket cameras to measure vibrations and displacements

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Analysis of vibrations and displacements is a hot topic in structural engineering. Video cameras can provide good accuracy at reasonable cost. Proper system configuration and adequate image processing algorithms provide a reliable method for measuring vibrations and displacements in structures. In this communication we propose using a pocket camera (CASIO) for measuring small vibrations and displacements. Low end cameras can acquire high speed video sequences at very low resolutions. Nevertheless, many applications do not need precise replication of the scene, but detecting its relative position. By using targets with known geometrical shapes we are able to mathematically obtain subpixel information about its position and thus increase the system resolution. The proposal is demonstrated by using a circular and elliptic targets on moving bodies The used method combines image processing and least squares fitting and the obtained accuracy multiplies by 10 the original resolution. Results form the low-end camera (400) working at 224x168 px are compared with those obtained with a high-end camera (10000) with a spatial resolution of 800x560 px. Although the low-end camera introduces a lot of noise in the detected trajectory, we obtained that results are comparable. Thus for particular applications, low-end pocket cameras can be a real alternative to more sophisticated and expensive devices.

8436-25, Session 7

Subjectively optimised multi-exposure and multi-focus image fusion with compensation for camera shake

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Multi-exposure image fusion algorithms are used for enhancing the perceptual quality of an image captured by sensors of limited dynamic range. This is achieved by rendering a single scene based on multiple images captured at different exposure times. Similarly, multi-focus image fusion is used when the limited depth of focus of a selected focus setting of a camera results in parts of an image being out of focus. The solution adopted is to fuse together a number of multi-focus images to create an image that is focused throughout, specially. In this paper we propose a single algorithm that can perform both multi-focus and multi-exposure image fusion.

One practical problem overlooked by existing algorithms for multi-exposure and multi-focus image fusion is the compensation required to correct possible multi-dimensional camera shake, which can result in adverse perceptual quality issues as non-corresponding regions may be fused. In this paper we propose a novel approach in which a set of unregistered multi-exposure/focus images is first registered and before being fused. The registration of images is done via identifying matching keypoints in constituent images using Scale Invariant Feature Transforms (SIFT). The RANdom SAmple Consensus (RANSAC) algorithm is used to identify inliers of SIFT key points removing outliers that can cause errors in the registration process. Finally we use the Coherent Point Drift (CPD) algorithm to register the images, preparing them to be fused in the subsequent fusion stage.

For the fusion of images, a novel approach based on an improved version of a Wavelet Based Contourlet Transform (WBCT) is used. The WBCT decomposes the multi/focus exposure images into low and high frequency sub-bands, which allow differentiating and selecting the best areas of the sub-bands according to a fusion rule proposed and adopted. One of the shortcomings of using existing WBCT based algorithms is that the low frequency sub-band of the fused image is formed using the average of the low-frequency sub-bands of the constituent images. However our experiments revealed that if this approach is used, the intensity of the image, as a result of the average of the set of multi-exposure images will ensure that the clipped areas (dark and bright) will have the right intensity, but the rest of the image's intensity will become flat, producing a hazy effect. In order to solve this problem, a fusion mask generated by the calculation of the energy of the high frequency contourlet sub-bands is used to fuse the low-pass wavelet sub-bands. In the proposed approach, the fusing mask is blurred with a Gaussian kernel having standard deviation of 1.3.

We provide experimental results to prove that the proposed algorithm is capable of registering and fusing a set of multi-exposure and multi-focus images taken in the presence of camera shake. A number of standard test image sets and newly captured sets of images with multi-dimensional (translational and rotational) camera shake are used in our experiments to enable the performance to be compared with existing algorithms.

8436-26, Session 7

Subjectively optimised H.264 multi-view video coding for viewing in auto-stereoscopic displays

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Auto-stereoscopic displays capable of producing perception of depth without glasses are entering the consumer market slowly by steadily. At present these displays have been limited to small size screens. In the future applications demanding the use of larger auto-stereoscopic displays will mean that existing known artefacts of large displays will have to be minimised if not entirely eliminated.

In this paper we evaluate the subjective performance of a state-of-the-art large screen (42") auto-stereoscopic display. We identify the problem of lack of contrast of viewed images due to the nature of the design of the lenticular display, needs to be addressed if video content is to provide an acceptable level of subjective quality. To this end we propose the use of a local energy based histogram equalisation approach to enhance contrast and to bring out detail in under exposed areas. We carry out subjective tests to prove that the proposed approach is effective in improving the subjective quality.

We further identify that coding artefacts are the key reasons for subjective quality loss. We propose a multi-objective optimisation approach for coding parameter selection of a H.264 MVC CODEC in which the combined encoder, decoder set up is optimised under multiple objectives/constraints related to rate, distortion, CPU cycles and memory usage. We first use extensive profiling of the H.264 MVC CODEC to identify the coding parameters that will have a significant impact on the above constraints. We subsequently used a genetic algorithm based approach to optimise the H.264 MVC codec producing coding parameter sets that results in the CODECs optimal performance, especially in subjective quality perception.

Throughout our investigations new approaches to subjective quality testing of multi-view images are established based of the subjective quality evaluation procedures set up by the international standardisation bodies for monoscopic videos. The paper will provide details of the established procedures. For a selected set of 5 multi-view videos, optimal coding parameter sets are identified following the above procedure and presented.

8436-27, Session 7

Data driven identification and aberration correction for model-based sensorless adaptive optics

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Wavefront sensorless adaptive optics is considered in many applications where the deployment of a dedicated wavefront sensor is inconvenient, such as in fluorescence microscopy. Here, aberration correction is achieved by sequentially changing the settings of the adaptive optical element until a predetermined cost function is optimised. Examples of such cost functions are, among others, sharpness measures for images and the amount of fluorescence emitted in fluorescence microscopy.

Model free approaches have been investigated in order to optimise a selected cost function. These include generic stochastic optimisations, stochastic gradient descent algorithms and the Nelder-Mead simplex method. Unfortunately, such general optimisations require a large number of measurements of the cost function so as to converge to an acceptable solution. The amount of necessary measurements is a critical factor as far as the acquisition speed is concerned, especially in scanning image acquisition settings. In addition, in fluorescence microscopy, the detrimental effect of phototoxicity and photobleaching is proportional to the number of measurements which are necessary for aberration correction.

Alternative methodologies, based on models derived from first principles, allow for direct and deterministic optimisation procedures using a small amount of measurements of the cost function. Nonetheless, a drawback arises in the need to calibrate such models by resolving a set of unknown parameters. Such estimation is to be performed once only.

In this paper, a data driven identification procedure is proposed for arbitrary quadratic models. Such a procedure involves the solution of a semidefinite programme minimising the quadratic error between the output predicted by the model and the data acquired from real experiments. After the identification has been performed, aberration correction entails solving a linear system of equations and requires $N+1$ measurements of the cost function, where N is the number of aberration modes considered.

8436-28, Session 7

Video surveillance for monitoring driver fatigue and distraction

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Fatigue and distraction effects in drivers represent a great risk for road safety. The dimensions of fatality crashes due to these effects can be compared with other driver behavior related problems including drinking and speeding. In one hand, fatigue reduces the capacity to pay attention to the driving tasks. In the other hand, driving performance can be degraded by cognitive or visual distraction, where visual distraction poses the major risk. Behavior due to both, fatigue and distraction can be detected by monitoring visual information related to the driver performance such as facial expressions. Considerable research has been conducted in this field, but little combining both, fatigue and distraction, types of driver behavior problems. In both cases, image analysis of eye movements gives valuable information. Fatigue can be detected by analyzing closure and opening of eyes while distractions from the visual focus can be identified by following the eyes movement. Analysis of the eyes behavior can be combined with other visible evidences of fatigue and distraction to infer possible risk factors of accident. This information can be used to automate preventive alarms.

We present in this paper a system for monitoring fatigue and distraction in drivers by evaluating their performance using image processing. We extract visual features related to nod, yawn, eye closure and opening, and mouth movements to detect fatigue as well as to identify diversion of attention from the road. Mouth movement is included to identify effects of fatigue on speech. The combination of these features gives robustness to the system in preventing car accidents due to human factors.

Visual features are extracted by using histogram analysis and thresholding on a set features based on Haar functions. We use these features to measure eye and mouth opening, magnitude of nod and time of diversion from the road. To extract these features we first identify the zone of the head. Then we use a window around it, processing only this region to speed up the algorithm. We convert images between different color spaces to enhance the visual characteristics, which facilitate the extraction of the features.

An automatic alert is activated with a multilayer neural network, which uses the features as input. The use of a neural network permits to adapt the system to the driver by conducting a training step before driving to recognize facial expressions related to fatigue and distraction of the driver. This allows the system to adapt to any driver. The degree of the alert depends of the repeatability intensity of the signals given by the features. The system is designed using open source to allow adapting it according to the needs of users.

We achieve accuracy of 90% in terms of fatigue detection and 92% for distraction. The time of processing takes between 40 and 50 milliseconds. However, the system still reports dependency to illumination conditions which strong variability. Therefore, it currently operates only in environments exposed to natural sun light. To solve this, future research must be focused on exploring methods invariant to illumination conditions.

8436-29, Session 8

First proposal for a general description model of forensic traces

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In recent years, the amount of digitally captured traces at crime scenes increased rapidly. There are various kinds of such traces, like pick marks on locks, latent fingerprints on various surfaces as well as different micro traces. Those traces are different from each other not only in kind but also in which information they provide. Every kind of trace has its own properties (e.g., minutiae for fingerprints, or raking traces for locks) but there are also large amounts of metadata which all traces have in common like location, time and other additional information in relation to crime scenes. For selected types of crime scene traces, type-specific databases already exist, such as the ViCLAS for sexual offences, the IBIS for ballistic forensics or the AFIS for fingerprints. These existing forensic databases strongly differ in the trace description models.

For forensic experts it would be beneficial to work with only one database capable of handling all possible forensic traces acquired at a crime scene. This is especially the case when different kinds of traces are interrelated (e.g., fingerprints and ballistic marks on a bullet casing). Unfortunately, current research on interrelated traces as well as general forensic data models and structures is not mature enough to build such an encompassing forensic database. Nevertheless, recent advances in the field of contact-less scanning make it possible to acquire different kinds of traces with the same device. Therefore the data of these traces is structured similarly what simplifies the design of a general forensic data model for different kinds of traces.

In this paper we introduce a first common description model for different forensic trace types. Furthermore, we apply for selected trace types from the well established database scheme development process the phases of transferring expert knowledge in the corresponding forensic fields into an extendible, database-driven, generalised forensic description model. The trace types considered here are fingerprint traces, traces at locks, micro traces and ballistic traces. Based on these basic trace types, also combined traces (multiple or overlapped fingerprints, fingerprints on bullet casings, etc) and partial traces are considered.

8436-30, Session 8

Advanced techniques for latent fingerprint detection and validation using a CWL device

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The technology-aided support of forensic experts while investigating crime scenes and collecting traces becomes a more and more important part in the domains of image acquisition and signal processing. The manual lifting of latent fingerprints using conventional methods like carbon black powder is time consuming and very limited in its scope of application. New technologies for a contact-less and non-invasive acquisition and automatic processing of latent fingerprints, promise the possibilities to inspect much more and larger surface areas and can significantly reduce the amount of work. Furthermore, it allows multiple investigations of the same trace, subsequent chemical analysis of the residue left behind and the acquisition of latent fingerprints on sensitive surfaces without destroying the surface itself. In this work, a FRT MicroProf200 surface measurement device equipped with a chromatic white-light sensor CWL600 is used. The device provides a gray-scale intensity image and 3D-topography data simultaneously. While large area scans are time-consuming, the detection and localization of finger traces are done based on low-resolution scans. The localized areas are scanned again with higher resolution. Due to the broad variety of different surface characteristics the fingerprint pattern is often overlaid by the surface structure or texture. Thus, image processing and classification techniques are proposed for validation and visualization of ridge lines in high-resolution scans. Positively validated regions containing complete or sufficient partial fingerprints are passed on to forensic experts. The experiments are provided on a set of three surfaces with different reflection and texture characteristics and fingerprints from ten different persons.

8436-31, Session 8

Gait recognition under carrying condition: a static dynamic fusion method

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Gait recognition has gained increasingly attentions in recent years, unlike face or iris recognition, it can be applied in an unobtrusive fashion, which is suitable for surveillance and monitoring applications. However, when a person carries an object, such as a briefcase, conventional methods like baseline method (direct frame matching) or methods based on average silhouette/Gait Energy Image (GEI) do not always perform well, as the object carried is often mistakenly regarded as a part of the human body. To solve such a problem, in this work, the dynamic and the static regions are separated from the GEI. To define the dynamic regions, we

propose the Mean Absolute Difference from Exemplar (MADE) which encodes the relationship between each gait frame and the gait sequence it belongs to. The dynamic region mask is generated by the statistical analysis on all the MADEs in the gallery, and areas with greater variance are deemed as dynamic regions. The areas covering the head and the body in GEI are considered as static regions. After projecting each GEI into its corresponding static and dynamic regions, the static/dynamic features are then extracted from each region by using 2D_LDA (Linear Discriminant Analysis) which can project high dimensional data into lower dimension space with optimal class separability. For a probe gait sequence, its corresponding GEIs are projected into the static and dynamic subspaces, respectively. Euclidean Distance is then employed as a measurement of the dissimilarity between the current probe and each class in gallery. The final decision of the classification result is based on the fusion of dissimilarity scores of both the static features and the dynamic features. We carry out experiments on the benchmark USF (University of South Florida) HumanID database by using the proposed static/dynamic fusion method. For the experiments under carrying condition, the average rank1 recognition rate is 79%, which is higher than most of the published gait recognition approaches.

8436-32, Session 8

Performance analysis of digital cameras versus chromatic white light (CWL) sensors for the localization of latent fingerprints in crime scenes

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In future applications of contactless acquisition techniques for latent fingerprints the automatic localization of potential fingerprint traces in crime scenes is required. For example, the amount of gathered data of a detailed scan chromatic white light (CWL) sensor with a resolution of 2540 ppi of an area of one square centimeter is 3.81 megabytes. Thus, especially for large scale crime scenes a detection of Regions-of-Interest is necessary to reduce the amount of acquired data. For that, various localization approaches using a CWL sensor for fast low resolution coarse scans are introduced in prior work and are still subject to research, too. However, the localization using this technique is surface dependent and time consuming for large crime scenes because every dot needs to be measured separately. Of course, the application of multiple CWL sensors might reduce the necessary acquisition time. For example, a camera-based approach might be an alternative technique that should be significantly faster due to the virtually instant acquisition of larger areas of the crime scene within a single image. Our goal is to study the application of a camera based approach [1] comparing with the performance of CWL techniques for the latent fingerprint localization in coarse and detailed scans. Furthermore, we briefly evaluate the suitability of the camera-based acquisition for the detection of malicious fingerprint traces using an extended camera setup in comparison to [2]. Our experimental setup includes three different digital single-lens reflex (DSLR) cameras with different sensor resolutions and a FRT MicroProf200 surface measurement device with CWL600 sensor. We apply at least two fingerprints to each surface in our test set. For that we use 8 different either smooth, textured and structured surfaces to evaluate the detection performance of the two localization techniques using different pre-processing and feature extraction techniques. Printed fingerprint patterns as reproducible but potentially malicious traces are additionally acquired and analyzed on foil and compact disks.

Our results indicate positive tendency towards a fast localization using the camera-based technique. All fingerprints that are located using the CWL sensor are found using the camera. However, the size of the area for the detailed scan for each potential latent fingerprint is usually slightly larger if the camera is used for the localization. Therefore, it is required to optimize the feature extraction and classification. Furthermore, the required acquisition time for each potential fingerprint needs to be estimated to determine the time-savings of the camera-based localization approach throughout the entire acquisition of traces.

The analysis of camera images of printed fingerprint patterns shows positive tendencies, too. However, only small sections of the fingerprint are sharply acquirable within a single photo, large sections of the image are usually blurred due to the depth of field of the camera lens.

References

[1] Lin, S.-S., Yemelyanov, K. M., Edward N. Pugh, J., and Engheta, N., “Polarization-based and specular-reflection-based noncontact latent fingerprint imaging and lifting,” J. Opt. Soc. Am. A 23, 2137-2153 (Sep 2006).

[2] Kiltz, S., Hildebrandt, M., Dittmann, J., Vielhauer C., and Kraetzer, C., “Printed fingerprints: a framework and first results towards detection of artificially printed latent fingerprints for forensics,” Proc. SPIE 7867, 78670U (2011); doi:10.1117/12.872329

8436-33, Session 8

Environmental impact to multimedia systems on the example of fingerprint traces aging behavior at crime scenes

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In the field of crime scene forensics, current methods of evidence collection, such as the acquisition of shoe-marks, tire-marks, palm-prints or fingerprint traces are in most cases still performed in an analogue way. For example, fingerprint traces are captured by powdering and sticky tape lifting, ninhydrine bathing or cyanoacrylate fuming and subsequent photographing. The photographed images of the evidence are then further processed by forensic experts.

With the upcoming use of new multimedia systems for the digital capturing and processing of crime scene traces in forensics, higher resolutions can be achieved, leading to a much better quality of forensic images. Furthermore, the fast and mostly automated preprocessing of such data using digital signal processing techniques is an emerging field. Also, by the optical and non-destructive lifting of forensic evidence, traces are not destroyed and therefore can be re-captured, e.g. by creating time series of a trace, to extract its aging behavior and maybe determine the time when a trace was left.

However, such new methods and tools face different challenges, which need to be addressed before a practical application in the field. Based on the example of fingerprint age determination, which is an unresolved research challenge to forensic experts since decades, we want to evaluate the environmental influences on the aging property of traces obtained by such a new optical and contactless measurement device in this paper. To underline the great potential of such new lifting tools, we have shown in prior work that using a Chromatic White Light (CWL) sensor, a characteristic logarithmic aging tendency can be observed for latent fingerprint traces from crime scenes, which is a first feature showing potential to finally solve this important research issue. Based on such example, we investigate in this paper the influence of different environmental factors on the quality of the resulting aging signal obtained by the CWL image sensory. By analyzing 864 images from 48 different fingerprint traces under 16 different environmental conditions, such as changing temperatures, humidity, vibrations, wind or UV-radiation, we show the challenges that arise for such new multimedia systems capturing and processing forensic evidence, which need to be addressed for an adequate image recovery from the sensor data and a correction of distortions. We discuss where distortions might be caused by environmental influences on the aging property of fingerprint traces and where they might influence the image sensory. We also propose possible measures to improve the overall accuracy of the aging tendency by controlling the surroundings of a trace or by improving the image sensory.

8436-34, Poster Session

Legally compatible design of digital dactyloscopy in future surveillance scenarios

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[This submission is intended for this special session on “Challenges in Signal Processing for Forensics”.] - Innovations in multimedia systems have an impact on our society, in particular, if they are applied to surveillance. For example surveillance camera systems which combine video and audio information are influencing our everyday life. Currently a new sensor system for capturing fingerprint traces is being researched [1]. It combines greyscale images to determine the intensity of the image signal, on one hand, and topographic information to determine fingerprint texture on a variety of surface materials, on the other. This research proposes new application areas: automated capture of fingerprints at crime scenes for court evidence as well as routine scanning of fingerprints on luggage at the airport in order to establish suspicious behavior or identify known criminals. This surveillance application shows that due to the development of new sensors, information can be captured by automatic means in new situations of everyday life. In consequence, the police and private security services can observe and check a large number of persons. This increase of police observation creates opportunities and risks for society. Therefore it is necessary to design multimedia technology for surveillance by taking the law into account [1] [2] [3] [4]. This is not only relevant for the design of the new sensor which acquires images but also the interaction with connected systems such as existing database systems storing reference data with which the acquired data is compared. While the surveillance application will not be realized in the short term, apparently, fundamental rights will be involved in the future. To ensure protection of fundamental rights, this paper shows proposals for a system design that is compatible with high-level legal requirements. Using German constitutional law as an example (which in the field of data protection is equivalent to other European countries), this papers aims at raising awareness of the privacy impact of multimedia systems on society and fostering responsible technology development in the photonics research and application communities.

[1] Mario Hildebrandt, Jana Dittmann, Matthias Pocs, Michael Ulrich, Ronny Merkel, Thomas Fries: Privacy preserving challenges: New Design Aspects for Latent Fingerprint Detection Systems with contact-less Sensors for Future Preventive Applications in Airport Luggage Handling. Proceedings of BioID 2011, Springer Lecture Notes on Computer Sciences (LNCS) Vol. 6583, Springer, Berlin 2011, 286.

[2] Monika Desoi, Matthias Pocs, Benjamin Stach: Biometric Systems in Future Crime Prevention Scenarios - How to Reduce Identifiability of Personal Data, in Brömme, A./Busch, C.: BIOSIG 2011. Proceedings - International Conference of the Biometrics Special Interest Group, Bonn 2011, 259-266.

[3] Matthias Pocs: Abgleich im Erfassungsgerät, in: Schartner, P./Taeger, J. (Hrsg.): Tagungsband D-A-CH Security 2011, syssec 2011, 346-360.

[4] Gerrit Hornung, Monika Desoi, Matthias Pocs: Biometric Systems in future preventive Scenarios - Legal Issues and Challenges, in: Brömme, A. / Busch, C. (Hrsg.), BIOSIG 2010. Proceedings of the Special Interest Group on Biometrics and Electronic Signatures, Bonn 2010, 83-94.

8436-35, Poster Session

The design of equipment for optical power measurement in FSO link beam cross-section

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The free space optical links have found their major application in today’s technological society. The demand for quality broadband is a must for all types of end users in these times. Because of the large jamming from wireless radio networks in non-licensed ISM bands, the free space optical links provide bridging of some densely populated urban areas. Their advantage is the high transmission rate for relatively long distances. However, the disadvantage is the dependence of free space optical links on atmospheric influences. Aired collimated optical beam passes through the atmospheric transmission environment and by its influence cause the deformation of the optical beam. Author’s team decided to construct a special measuring device for measurement of optical power in FSO link beam cross-section. The equipment is mobile and can be rearranged and adjust according to the given location and placement of the FSO link at any time. The article describes the individual structural elements of the measuring equipment, its controlling and application for evaluation and adjustment of measuring steps. The graphs from optical power measurements in the beam cross-section of professional FSO links are presented at the end.

8436-36, Poster Session

Improvement method of the optical MTF by using Bayes theorem and application results to a rod lens optical system

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Gradient-index (GRIN) lenses have excellent optical properties that are not generally observed in the case of homogeneous lenses. Hence, GRIN lenses are used to fabricate new optical elements that have promising applications in optical information processing and optical communication. For example, it is widely used for scanner, fax machines and copiers etc. One of the low cost fabricating method of these lenses involves pulling up the core fiber vertically from a polymer solution whose refractive index has been adjusted to the desired value. But in fact, the refractive-index distribution is not ideal because of several factors in manufacturing. When a GRIN lens has the refractive-index distribution which is not ideal, it degrades MTF extremely.

In this paper, we studied the picture reconstruction by using Bayes’ theorem. Bayes’ theorem is applied to the degraded picture obtained in an experiment with the plastic rod lens, and as a result MTF has extremely improved.

First, spatial distribution of PSF(Point Spread Function) is calculated from the refractive index distribution inside a rod lens. The 4096 PSF(s) of spatial distributions are obtained by this calculation. By applying image processing using the Bayes’ theorem, MTF becomes about 100% after the application, even if MTF is 48%. These researches show that Bayes’ theorem is very effective in image restoration.

8436-37, Poster Session

Development of large capacity holographic memory using blue laser

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Holographic memory has been researched for next generation large capacity memory. Photo polymer is used for recording medium. Large capacity holographic memory system is suitable for use in an archive memory. At present hard disk drive and magnetic tape are used in center system as an archive memory. If we use holographic memory for this application, large data capacity of 1TB~10TB/disk will be required in the future.

To realize such a large capacity memory technology ,we studied the method to do an angle multiplexing by using a spherical reference wave. By using thick film medium with spherical reference wave, it makes possible to use both angle multiplexed and shift multiplexed recording. The density growth can be expected by overwriting the hologram. In addition, a further large capacity can be expected by using the transmission type together with the reflection type hologram recording.

In this paper, the result of verifying fundamental proof of these methods

was reported by the record reproduction simulation and the experiment. In experiment we use blue laser with wavelength of 405nm and photo polymer with 1.5mm film thickness. By using these methods, the recording density of more than 1Tb/ is achieved.

8436-38, Poster Session

Optical correlator optimized for medical applications

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We have previously developed a compact slot-in-type optical correlator. The optical correlator used in this study was a compact joint transform correlator This JTC, which is the optical system used to calculate the correlation between two patterns displayed using Fourier-transforming lenses, treats the data in parallel. Some optical parts were changed to eliminate stray light from the optical components in the JTC in this study. For example, beam splitter in optical correlator was changed to wedge half mirror to eliminate stray light. Using wedge half mirror, stray light was displaced from the optical axis. Therefore, it was collected light out-of plane to the CMOS camera.

The color and texture data were transformed to an x-y chromaticity diagram and a luminance histogram, respectively. The tumor cells have a high affinity to dye and show hyperplasia when compared to normal cells. These differences between normal and tumor cells have a large effect on color and luminance information in the images. Here, the luminance information corresponds to the texture of the image [1]. From this, two-dimensional patterns describing the color and luminance information of cell images were deduced so that they could be retrieved with the correlator. The x-y chromaticity diagram were converted from the gray values of red, green, and blue in each pixel of the images taken with a digital camera into patterns on a color chart. The color patterns extracted from tumor cell images were larger than those from normal cell images. A luminance histogram is a 2D pattern in which the x-axis and y-axis represent the luminance value and pixel number, respectively. The luminance histogram converted from tumor cell images increases in the low luminance range. The y-axis of luminance histogram was logarithmically-transformed to emphasize the low luminance range. Their patterns are retrieved by the JTC as shape information.

Using the 2D patterns of color and luminance information, the images of normal and tumor cells were retrieved with the correlator. The pattern of normal cell image was used as the reference, and various cell images were retrieved. The intensity of the cross-correlation spot was high when the retrieved pattern coincided with the reference, while the intensity was low when the two compared patterns were different. In the colour distinction with x-y chromaticity diagram, the intensity of the correlation signal among normal cell was high, but that among tumor cell was a little high or low. In the texture distinction with the luminance histogram, the intensity of the correlation signal among normal cell was high or little high, but that among tumor cell was low. Finally, using the optical correlator improved and optimized for medical applications, this study was demonstrated the results that the tumor cells were then clearly distinguished from a large number of cells by combining the color and texture retrieval results.

[1] I. Motoyoshi et al., "Image statistics and the perception of surface qualities," Nature, Vol. 447, 206-209 (2007).

8436-39, Poster Session

Spectral characteristics of fiber couplers for FTTx networks

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This article deals with spectral characteristics measurement of fiber couplers which are used for FTTx networks. Due to WDM systems we are able to communicate with several wavelengths at a time. In xPON systems the data transmission runs at wavelengths 1310 nm, 1490 and 1550 nm, in case of using singlemode fibers, or at 850 nm and 1300 nm in case of using multimode fibers. The target of this work is a testing how the individual parameters of fiber coupler behave whether broad spectrum light source is connected to the input. In sum it was measured four most often used fiber couplers, fiber coupler in port configuration 1x2 with coupling ratio 50/50%, fiber coupler in port configuration 1x2 with coupling ratio 30/70%, fiber coupler in port configuration 1x2 with coupling ratio 10/90% and fiber coupler in port configuration 1x4 with coupling ratio 4x 25%. For these fiber couplers it was set insertion losses, coupling ratios, homogeneities and total losses by using a broad spectrum light source. The results are valuable information for companies which deal with optical networks.

8436-40, Poster Session

Change image detection under unknown affine transformations of intensity

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The detection of changes in images plays a significant role in many computer vision applications such as visual surveillance systems, remote sensing, medical diagnosis and treatment, civil infrastructure etc. One of the basic premise is to separate changes caused by objects of interest from other changes due to differences in illumination, viewing angles and so on. Here, we address the problem of image change detection in the presence of unknown non-uniform intensity transformations. Multiplicative and additive uniform intensity transformations considered are solved using operators based on local vector space geometry. We now generalize this method for situations where a linear intensity gradient across the image can also be present. This situation can occur in active illumination systems or when curved surfaces are illuminated from a source at an angle away from the line of sight. The method proposed is based on calculating geometrical functions by projecting the local vectors upon a certain subspace defined by the reference. Various experiments are carried out to confirm the correct image detection. In addition, all difference local operators are defined in terms of correlations which can be useful for optical implementations using conventional Vander Lugt or joint transform correlators.

8436-42, Poster Session

View-through characterization of translucent fabrics based on opto-digital image analysis

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Translucent fabrics transmit light but provide sufficient diffusion to eliminate perception of distinct images. Traditional translucent woven fabrics include organdie, silk chiffon and muslin cotton, among many others. When such materials are used in curtains they provide even light transmission, solar protection and natural lighting, with a wide range of degrees of view-through. Since all these properties can be referred to the concepts of privacy, space and boundary, they are highly appreciated in interior design and architecture. The conventional metrics used to characterize a translucent fabric are the UV or Visible light transmission, the cover factor and the shading coefficient. In this work we propose to use other metrics commonly utilized to characterize imaging systems such as the modulation transfer function (MTF). When looking through a curtain, the translucent fabric can be modeled as a low-pass filter that is combined with human eye imaging system. We replace our visual system by a high-quality still photographic camera. The MTF curve allows one to characterize the view-through performance of the translucent fabric in a more realistic way than the simple light transmittance, cover factor or shading coefficient. Two object tests, placed at a distance from the fabric, have been used to experimentally derive the MTF of the whole imaging system (translucent fabric and camera): a USAF test and a slanted edge test. In the latter case the Line Spread Function is firstly obtained and the MTF estimated. The method has been applied to a set of translucent fabrics with different thread diameters and densities. From the MTF curves obtained using both tests, the transparency of the fabrics is objectively and quantitatively characterized in terms of view-through. The results are presented and discussed.

8436-43, Poster Session

Measuring image quality performance on image versions saved with different file format and compression ratio

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Digitization of existing documents containing images is an important body of work for many archives ranging from individuals to institutional organizations. The methods and file formats used in this digitization is usually a trade off between budget, file volume size and image quality, while not necessarily in this order. The use of most commons and standardized file formats, JPEG and TIFF, prompts the operator to decide the compression ratio that affects both the final file volume size and the quality of the resulting image version. Additionally, the file conversion can be done at the primary digitization stage, camera or scanner, or as a postproduction step, by means of image processing software. In both cases, the indicative that identifies the compression ratio used, follows often a proprietary code don't standardized or related within devices and/or software. The evaluation of the image quality achieved by a system can be done by means of several measures and methods, being the Modulation Transfer Function (MTF) one of most used. The methods employed by the compression algorithms affect in a different way the two basic features of the image contents, edges and textures. Those basic features are too differently affected by the amount of noise generated at the digitization stage. Therefore, the target employed in the measurement should be related with the features usually presents in general imaging. Specially when the file format and compression are generated by the digitization device, there can be done also some internal image processing intended to counteract any device blemishes; edge enhancement and noise reduction algorithms are the most frequently used. Provided that the frequency content of the digitized images is diverse, the grade of image quality affectation is diverse too, as well as the kind of image features affected. In order to accomplish with the needs early stated, the MTF measurement has been done by two separate methods using the slanted edge and dead leaves targets respectively. While the slanted edge method is a well-recognized indicator of the whole image quality level, an excessive edge enhancement can be reported as a better quality image because the measure is being done over an edge. Conversely, the dead leaves target is more prone to be sensible to the texture changes, as is described as a fine complementary result in these cases. This work presents a comparison between the results obtained by measuring the MTF of images taken with a professional camera system and saved in several file formats and compression ratios; those image versions have been generated by the camera firmware and on an external image processing software. The measurement results are shown and compared related with the respective file volume size.

8436-45, Poster Session

Process simulation in digital camera system

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Te goal of this paper is to simulate the functionality of a digital camera system. The simulations cover the conversion from light to numerical signal and the color processing and rendering. We consider the image acquisition system to be linear shift invariant and axial. The light propagation is orthogonal to the system. We use a spectral image processing algorithm in order to simulate the radiometric properties of a digital camera. In the algorithm we take in consideration the transmittances of the: light source, lenses, filters and the quantum efficiency of a CMOS (complementary metal oxide semiconductor) sensor. The optical part is characterised by a multiple convolution between the different points spread functions of the optical components. We use a Cooke triplet, the aperture, the light fall off and the optical part of the CMOS sensor. The electrical part consists of the: Bayer sampling, interpolation, signal to noise ratio, dynamic range, analog to digital conversion and JPG compression. We reconstruct the noisy blurred image by blending different light exposed images in order to reduce the photon shot noise, also we filter the fixed pattern noise and we sharp the image. Then we have the color processing blocks: white balancing, color correction, gamma correction, and conversion from XYZ color space to RGB color space. For the reproduction of color we use an OLED (organic light emitting diode) monitor. The analysis can be useful to assist students and engineers in image quality evaluation and imaging system design. Many other configurations of blocks can be used in our analysis.

I simulate, using images, the functionality of a visible light digital camera. I use Matlab for simulations of the images.

References

R. D. Fiete, Modeling the image chain of digital cameras, SPIE Press, 2010

G. C. Holst, T. S. Lomheim, CMOS/CCD Sensors and Camera Systems. SPIE Press, 2007

H. R. Kang, Computational Color Technology,SPIE Press, (2006)

F. Toadere, Conversion from light to numerical signal in a digital camera pipeline, Proc. SPIE, Volume 7821, 2010

8436-46, Poster Session

Texture analysis based on the Hermite transform for image classification and segmentation

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Texture analysis has become an important task in image processing because it is used as a preprocessing stage in different research areas including medical image analysis, industrial inspection, segmentation of remote sensed imaginary and multimedia indexing and retrieval. In order to extract visual texture features a texture image analysis technique is presented based on the Hermite transform. Psychovisual evidence suggests that the Gaussian derivatives fit the receptive field profiles of mammalian visual systems. The Hermite transform describes locally basic texture features in terms of Gaussian derivatives. Multiresolution combined with several analysis orders provides detection of patterns that characterizes every texture class. The analysis of the local maximum energy direction and steering of the transformation coefficients increase the method robustness against the texture orientation. This method presents an advantage over classical filter bank design because in the latter a fixed number of orientations for the analysis has to be selected. During the training stage, a subset of the Hermite analysis filters is chosen in order to improve the inter-class separability, reduce dimensionality of the feature vectors and computational cost during the classification stage. We exhaustively evaluated the correct classification rate of real randomly selected training and testing texture subsets using several kinds of common used texture features. A comparison between different distance measurements is also presented. Results of the unsupervised real texture segmentation using this approach and comparison with previous approaches showed the benefits of our proposal.

8436-48, Poster Session

Separation of high-resolution samples of overlapping latent

fingerprints using relaxation labeling

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The analysis of latent fingerprint patterns generally requires clearly recognizable friction ridge patterns. Currently, overlapping latent fingerprints pose a major problem for traditional crime scene investigation. This is due to the fact that these fingerprints usually have very similar optical properties. Consequently, the distinction of two or more overlapping fingerprints from each other is not trivially possible. While it is possible to employ chemical imaging to separate overlapping fingerprints, the corresponding methods require sophisticated fingerprint acquisition methods and are not compatible with conventional forensic fingerprint data.

A separation technique that is purely based on the local orientation of the ridge patterns of overlapping fingerprints is proposed by Chen et al. and quantitatively evaluated using off-the-shelf fingerprint matching software with mostly artificially composed overlapping fingerprint samples, which is motivated by the scarce availability of authentic test samples.

The work described in this paper adapts the approach presented by Chen et al. for its application on authentic high resolution fingerprint samples acquired by a contact-less measurement device based on a chromatic white light (CWL) sensor. An evaluation of the work is also given, with the analysis of all adapted parameters. Additionally, the separability requirement proposed by Chen et al. is also evaluated for practical feasibility. Our results show promising tendencies for the application of this approach on high-resolution data, yet the separability requirement still poses a further challenge.

8436-49, Poster Session

High speed image techniques for construction safety net monitoring in outdoor conditions

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The behaviour of a construction safety net and its supporting structure was monitored with a high speed camera and image processing techniques. A 80 kg cylinder was used to simulate a falling human body from the upstairs floor of a building under construction. The cylinder rolled down over a ramp until it reaches the net. The behaviour of the net and its supporting structure was analysed through the movement of the cylinder once it reaches the net. The impact was captured from a lateral side with a high speed camera working at 500 frames per second. In order to obtain the cylinder position each frame of the sequence was binarized. Through morphological image processing the contour of the cylinder was isolated from the background and with a Hough transform the presence of the circle was detected. With this, forces applying on the net and the supporting structure have been described, together with the trajectory of the cylinder. All the experiment has been done in a real structure in outdoors location. Difficulties found in the preparation on the experiment and in extracting the final cylinder contour are described and some recommendations are giving for future implementations.

8436-50, Poster Session

Surface classification and detection of latent fingerprints based on 3D surface texture parameters

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In the field of latent fingerprint detection in crime scene forensics the classification of surfaces has importance. A new method for the scientific analysis of image based information for forensic science was investigated in the last years. Our image acquisition based on a new sensor using Chromatic White Light (CWL) with a lateral resolution up to 2 µm. The used FRT-MicroProf 200 CWL 600 measurement device can capture high-resolution intensity and topography images in an optical and contact-less way. In prior work, we have suggested to use 2D surface texture parameters to classify various materials, which was a novel approach in the field of criminalistic forensic using knowledge from surface appearance and a chromatic white light sensor. A meaningful and useful classification of different surfaces, as required in this project, is not existent.

In this work, we want to extend such considerations by the usage of fourteen 3D surface parameters, called 'Birmingham 14'. In our experiment we define these surface texture parameters and use them to classify ten different materials in this test set-up and create specific material classes. Further it is shown in first experiments, that some surface texture parameters are sensitive to separate fingerprints from carrier surfaces. So far, the use of surface roughness is mainly known within the framework of material quality control. The analysis and classification of the captured 3D-topography images from crime scenes is important for the adaptive preprocessing depending on the surface texture. The adaptive preprocessing in dependency of surface classification is necessary for precise detection because of the wide variety of surface textures. We perform a preliminary study in usage of these 3D surface texture parameters as feature for the fingerprint detection. In combination with a reference sample we show that surface texture parameters can be an indication for a fingerprint and can be a feature in latent fingerprint detection.

8436-51, Poster Session

High dynamic range video transmission and display using standard dynamic range technologies

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Although advances are being rapidly made in capturing of High Dynamic Range (HDR) images/video, there remain problems with regards to transmitting and displaying the HDR image data. Current consumer level displays are designed to only display images with a depth of 8 bits per pixel. Typical HDR images can be 10 bits per pixel and upwards, leading to the first problem, how to display HDR images on Standard Dynamic Range (SDR) displays. This is linked with a further problem, that of transmitting the HDR data to the SDR devices, due to the fact that most state-of-the-art image/video coding standards deal with only SDR data. Further, as with most technologies of this kind, current HDR displays are extremely expensive. Furthermore, media broadcast organisations have invested significant sums of money into their current architecture and are unwilling to completely change their systems at further cost.

This paper aims to resolve the above challenges by presenting a missing link between capture and end display devices. We show that it is possible to extract data within a 8 bit range while making use of the additional data in a 10 bit image to enhance the image thereby improving the viewing experience for the viewer. In other wards our proposed method also allows the SDR information to be transmitted with a Tone Map that allows the HDR image to be reconstructed. This allows for

both backward compatibility and HDR compression. To further ensure backward compatibility, the H.264 codec is used for coding the video data as this has become the industry standard in video coding at present. Both SDR video data and tone map data are coded and transmitted using H.264.

These input mages/frames are translated from RGB to YCbCr as the processing is applied only to the intensity layer, thus preserving colour information. After applying a bilateral filter to the image, the resulting large-scale layer is enhanced by applying a novel Adaptive Tone Mapping method. The corresponding detail layer maintains edge and texture information. Our method uses Otsu's thresholding model to divide the histogram into three regions. The thresholds obtained determine the tone map curve that is applied to each region of the image, allowing hidden details to be lifted from shadows and over exposed areas.

Finally, the data from the light sensor of a typical display is used as a scalar to influence the magnitudes of the tone mapping curves applied to the image. This has the effect of maintaining an ideal image quality no matter the intensity of the light being received at the display device.

We provide details of the system design on a Mac environment, including the design of the tone mapping approach, encoder, ambient and backlight sensing, and inverse tone mapping approach. Further we show that a number of approaches can be made use to make the proposed procedure work real-time.

8436-52, Poster Session

Segmentation of 4D cardiac computer tomography images using active shape models

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This paper describes a segmentation method of time series of 3D cardiac images based on deformable models. The goal of this work is to extend active shape models (ASM) of tree-dimensional objects to the problem of 4D (3D + time) cardiac CT image modeling. The segmentation is achieved by constructing a point distribution model (PDM) that encodes the spatio-temporal variability of a training set, i.e., the principal modes of variation of the temporal shapes are computed using some statistical parameters. Since the manual segmentation process of each example shape is a tedious and time consuming task, we use an automatic approach for landmark generation in which correspondence among points are found. An active search is then used in the segmentation process where an initial approximation of the spatio-temporal shape is given, and the gray level information in the neighborhood of the landmarks is analyzed. The starting shape is able to deform so as to better fit the data, but in the range allowed by the point distribution model. Algorithms for automatic initialization based on pixel classification are explored as well. Several time series consisting of eleven 3D images of cardiac CT are employed for the validation of the method. Results are compared with manual segmentation made by an expert and other methods. The proposed application can be used for the clinical evaluation of the mechanical function of the left ventricle.

8436-53, Poster Session

Filtering and detection of low contrast structures on ultrasound images

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In this paper, we propose a detection method of low contrast structures in medical ultrasound images. Since noise speckle makes difficult the analysis of ultrasound images, a wavelet-based filtering approach is used for the enhancement and noise reduction. This technique works based on the supposition that the speckle noise is a random variable with a Rayleigh distribution and depends only on the characteristics of the ultrasound device. A Bayesian estimator is then used at subband level for pixel classification. The estimator parameters are calculated using an adjustment method derived from the first and second statistical moments. We consider a statistical detection model that depends on the variable size and contrast of the image speckle. The method has been evaluated and simulated using several real and synthetic ultrasound images. The proposed algorithm can be helpful for automatic detection of tumors in mammographic ultrasound images. This approach is finally compared quantitatively and qualitatively with other previously published methods applied on ultrasound medical imagery.

8436-54, Poster Session

Arbitrary micro phase-step digital holographic microscopy

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This paper applies the Mach-Zehnder interferometer with an objective lens and an offset lens to magnify the wavefront of an object image, while compensating for the quadratic phase caused by the objective lens and achieving digital holographic microscopy [1]. The single-exposure method and simple arbitrary micro phase step (AMPS) approach are applied to suppress the zero-order and conjugate image interferences caused by holograph reconstruction. Through this process the best conditions for conjugate imaging suppression can be identified via the relative light intensity distribution and noise suppression of the numerically reconstructed object wavefront.

This study replaces the traditional high cost piezoelectric converter (PZT) phase modulation with a simple, low cost cover glass to accurately trace the phase modulated reference wave. An experiment was used to prove that the AMPS method can accurately estimate and effectively suppress conjugate image interference. These experiments confirm that when $= \pi / 2$, the background noise suppression is relatively better. Using a simple numerical calculation the information carried by the object wave can be effectively enhanced and thereby the background noise can be suppressed to optimize the image reconstruction effect.

8436-56, Poster Session

Fabrication of chalcogenide glass molding lens for thermal imaging applications

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Thermal imaging in the 8 to 12 um wavelength range was once the sole domain of the military because of the high cost of the hardware (mainly detector). With the recent development of less costly uncooled infrared detector technology, thermal cameras have been applied to a wide variety of commercial applications such as night driving, night security, and sleep lab monitoring. However, the optics, made of expensive single-crystal materials such as Ge, Si, and ZnSe, still prohibit a breakthrough for high-volume commercial systems. In addition, the key process used thermal imaging lens fabrication is single-point diamond turning (SPDT). SPDT is an expensive operation and is not compatible with high volume applications. Therefore, it is unlikely that the cost of single-crystal lenses fabricated with SPDT can be dramatically decreased to meet the price target for applications such as night vision for cars. As a potential solution to this problem, the fabrication of IR lenses using chalcogenide glasses has been studied in recent years. Because chalcogenide glass is cheaper than the crystalline materials and moldable vitreous material, the use of a chalcogenide glass lens would be an effective way to reduce the cost of IR optics in high-volume applications. Molding is much cheaper than mechanical turning. However, the physical properties of chalcogenide glasses are very different from the optical glasses commonly used in glass molding. Therefore, extensive studies are required to determine the optimum parameters for molding this glass.

We report on fabrication of chalcogenide glass molding lens for car

night-vision and on the evaluation of the molded chalcogenide glass lens. Molding conditions of the lens was determined by thermal analysis; molding temperature, heating time. The moldability of chalcogenide glass was characterized through defects of lens surface and transcription properties of the mold's surface. In addition, both IR transmittance and XRD patterns of the molded chalcogenide glass lens were evaluated to verify the compositional and structural stability of the glass material at the corresponding molding condition.

8436-57, Poster Session

Real-time portable system for fabric defect detection using an ARM processor

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Modern textile industry seeks to produce textiles as little defectives as possible since presence of defects can decrease the final price of products from 45% to 65%. Defect detection in fabrics permits to remove or in some cases correct defects reducing their presence in the final production, where the amount of defects per surface length defines the quality of the textile material.

Inspection to recognize defects in fabric production environments is mainly conducted in three stages: before production; during production and at the end of all. Traditionally, inspection tasks are performed by human experts. However, the subjective human inspection may result in errors that can severely affect production quality. Therefore, an active effort to offer more accurate inspection systems is being undertaken in developing automated mechanisms for inspection methods.

Automated visual inspection (AVI) systems, based in image analysis, have become an important alternative for replacing traditional inspections methods that involve human tasks mostly because they are inspired on human visual perception. An AVI system gives the advantage of repeatability when implemented within defined constrains, offering more objective and reliable results for particular tasks than human inspection.

There exist already AVI systems for the textile industry that detect defects in fabrics. Companies report more effectiveness and objectiveness using AVI, instead of human systems, reporting increases from 70% to 80% of average in terms of correct defect detection. Reproducibility and inspection speed are also reported to be higher using AVI systems. However, current systems are still expensive for small and medium companies. Besides, the systems are mostly dedicated for an specific stage of inspection.

Costs of automated inspection systems development can be reduced using modular solutions with embedded system, in which an important advantage is the low energy consumption.

Portable devices with specific tasks can be used in any on the inspection stages. Open architecture design, modularity and flexibility of embedded systems may permit the inspection to adapt to different stages within the manufacturing processes.

Among the possibilities for developing embedded systems, the ARM processor has been explored for acquisition, monitoring and simple signal processing tasks. In a recent approach we have explored the use of the ARM processor for defect s detection by implementing the wavelet. However, the speed of the preprocessing was not yet sufficient for real time applications.

In this approach we significantly improve the processing speed of the algorithm, by optimizing matrix operations in the ARM processor, such that it is adequate now for a real time application. The system was tested for defect detection using different types of defects. The paper is focused in giving a detailed description of the basis of the algorithm implementation, such that other algorithms may use of the ARM operations for fast implementations. In parallel research we are also exploring the uses of GPU for real time applications. Therefore, in further approaches we propose to combine the advantages of the ARM and the GPU processors to develop a real time, modular, efficient and low cost systems accessible for small and medium companies.

8436-58, Poster Session

Response of human visual system to various methods of stereoscopic projection

S. Vítek, Czech Technical Univ. in Prague (Czech Republic)

This contribution is focused on quantifying of the effect of various methods of stereoscopic projection on human visual system. It is well known that watching of the stereoscopic projection overload ocular vergence system - but this overload was not quantified in any relevant way. Our approach is based on comparing the eye movements (both visual tracking and EEG measurements) while observer is watching the simple natural scene and its computer model projected by various stereoscopic projection system. As a natural scene we used a wire cube (very raw volumetric display) at whose corners and crosses are located small sources of light (LED), so an observer can easily fix his gaze in various places in the space. Experiments were performed on the stereoscopic display with different principles: system with liquid crystal shutter glasses and system with passive glasses (both polarized and anaglyph). The virtual scene created in Blender which the viewer is observing on the stereoscopic display is an accurate model of the natural scene, including dimensions and timing of the lighting of the light sources. Our main goal (and further research as well) is to determine the critical parameters of a given scene which may reduce comfort while scene is displayed on the particular stereoscopic display.

8436-59, Poster Session

Can state-of-the-art HVS based objective image quality criteria be used for image reconstruction techniques based on ROI analysis?

P. Dostal, Czech Technical Univ. in Prague (Czech Republic)

Various image processing techniques in multimedia technology are optimized using visual attention feature of the human visual system, spatial non-uniformity causing that different locations in an image are of different importance in terms of perception of the image. In other words, the perceived image quality can mainly depend on the quality of important locations known as region of interest. The performance of such techniques is measured by subjective evaluation or objective image quality criteria. Many state-of-the-art objective metrics are based on HVS properties; SSIM, MS-SSIM based on image structural information, VIF based on the amount of information human brain can ideally gain from the reference image or FSIM utilizing the low-level features to assign the different importance to each location in the image. But still none of these objective metrics utilize the analysis of region of interest. We tried to answer the question if these objective metrics can be used for effective quality assessment of images reconstructed by processing techniques based on ROI analysis utilizing high-level features. In this paper authors present that the state-of-the-art objective metrics do not correlate well with subjective evaluation while the ROI analysis based demosaicing is used for reconstruction. The ROI data was computed from “ground truth” visual attention coordinates. The algorithm combing two known demosaicing techniques is proposed. The ROI location is taken into account to reconstruct the image regions in high quality while the rest of image is reconstructed with low quality. The color image reconstructed by this ROI approach was compared with selected demosaicing techniques by objective criteria and subjective testing. The qualitative comparison of the objective and subjective results indicates that the state-of-the-art objective metrics are still not suitable for evaluation image processing techniques based on ROI analysis and new criteria is needed.

8436-60, Poster Session

Real-time interactive projection system based on infrared structured-light method

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Interactive technologies have been greatly developed in recent years, especially in projection field. However, most interactive projection systems are based on special designed interactive pens or whiteboards at present, which is inconvenient and limits the improvement of user experience.

In this paper, we introduced our recent progress on theoretically modeling a real-time interactive projection system. The system permits the user to easily operate or draw on the projection screen directly by fingers without any other auxiliary equipment. Obviously, in order to obtain real-time smooth writing experience on the screen, the capture speed and the process speed are the main factors. Thus, in the experiment, we should make the background of the captured images clean and make the noise reduce for easy recognition of the fringes, which is the reason that the infrared patterns are used. The projector projects infrared striping patterns onto the screen and the CCD captures the deformational images due to the finger's block. We resolve the finger's position and track its movement by processing the deformational images in real-time. We can acquire the first deformational fringe on the finger by image processing; the middle point of the fringe can be as the position parameters of the fingertip. A new way to determine whether the finger touches the screen is proposed. The first deformational fringe on the fingertip and the first fringe at the finger shadow are the same one. The correspondence is obtained, so the location parameters can be decided by triangulation. We need only calculate the distance of the two fringes and needn't compute the height directly. By this way, we can determine whether or not the finger touches the screen directly, and that is easy and fast for data processing which is beneficial to get quick tracking speed. The simulation results are given, and errors are analyzed.

8436-61, Poster Session

Intra-Oral OCT: an in vivo assessment of ceramic inlays

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The investigation of dental materials, dental prostheses and their behaviour under certain conditions can be performed by in vitro methods which are invasive, meaning that any samples tested are destroyed being no longer of use after testing. Clinical studies can also be conducted mainly involving case reports or follow-ups which can reveal information on certain aspects regarding direct or indirect dental restorations but they stretch over longer periods of time and they don't allow detecting intrinsic defects or the lack of marginal fit in its early stages.

Our research focuses on implementing a new, non-invasive tool - optical coherence tomography which has the great advantage that any sample can be used if found adequate after investigation.

Until now, OCT has been only employed in in vitro studies. The aim of our study is to investigate ceramic inlays and their marginal fit using an experimental intra-oral Spectral OCT in order to attempt to detect any defects that can not be observed clinically and to verify the utility of this novel investigation alternative.

We selected 10 patients presenting a total of 16 posterior ceramic inlays. The restorations were not older than 24 months and they showed no visible technological/clinical defects at the time the investigation was performed.

All restorations were investigated by intra-oral OCT in the spectral domain working mode. Subsequently, the images were analyzed and defects were found within the ceramic material and also marginal gaps indicating the incipient failure of some of the restorations. These findings are very relevant for the practitioner since they offer information on the clinical behavior of the restorations and can respresent a useful hint on how often to schedule recalls. Using OCT as an in vivo investigating tool in dentistry is a new approach that opens an entirely new perspective on the clinical acceptability of dental restorations.

8436-62, Poster Session

Bone regeneration evaluation by optical coherence tomography and microCT methods

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Bone grafting is a commonly performed surgical procedure to augment bone regeneration in a variety of orthopaedic and maxillofacial procedures, with autologous bone being considered as the "gold standard" bone-grafting material, as it combines all properties required in a bone-graft material: osteoinduction (bone morphogenetic proteins - BMPs - and other growth factors), osteogenesis (osteoprogenitor cells) and osteoconduction (scaffold).

Material and methods. 10 rat femurs were used for this investigation. In each ones a 1 mm diameter hole were drilled and a bone grafting material was inserted in the artificial defect. The femurs were removed after one, three and six months. The defects repaired by bone grafting material were evaluated by optical coherence tomography working in Time Domain Mode at 1300 nm. Three dimensional reconstructions of the interfaces were generated. The validations of the results were evaluated by microCT. Synchrotron Radiation allows achieving high spatial resolution images to be generated with high signal-to-noise ratio. Use of X-rays delivered by Synchrotron Facilities has several advantages compared to X-rays produced by Laboratory or Industrial sources. These include: (i) a high photon flux which permits measurements at high spatial resolution; (ii) the X-ray source is tunable, thus allowing measurements at different energies; (iii) the X-ray radiation is monochromatic, which eliminates beam hardening effects; and (iv) parallel beam acquisition allows the use of exact tomographic reconstruction algorithms. In addition, Synchrotron Radiation allows acquisition of volumes at different energies and volume subtraction to enhance contrast.

Results and Conclusions. Evaluation of the bone grafting material/ bone interface with noninvasive methods such as optical coherence tomography could act as a valuable procedure that can be use in the future in the usual clinical techniques. The results were confirmed by microCT. Optical coherence tomography can be performed in vivo and can provide a qualitative and quantitative evaluation of the bone augmentation procedure.

8437-16, Poster Session

MTF measurements on real time for performance analysis of electro-optical systems

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The evaluation of Modulation Transfer Function (MTF) is one of the widely used methods for performance analysis of an optical system. The MTF represents a quantitative and direct measure of image quality and, besides being an objective test, it can be used on concatenated optical system. This paper presents the application of software called SMTF (Software Modulation Transfer Function), built in C++ and Open CV platforms for MTF calculation on electro-optical system. Through this technique, it is possible to develop specific method to measure on real time the performance of a digital fundus camera, an infrared sensor and an ophthalmological surgery microscope on the assemblage procedure to help the alignment of the complete optical system. Each optical instrument mentioned has a particular device to measure the MTF response, which is being developed. Then the MTF information assists the analysis of the optical system alignment, and also defines its resolution limit by the MTF graphic. The result obtained from the implemented software is compared with the theoretical MTF curve from the analyzed systems.

8437-17, Poster Session

Real-time shrinkage studies in photopolymer films using holographic interferometry

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Polymerisation induced shrinkage is one of the main reason why photopolymer materials are not widely used for holographic applications. The aim of this study was to evaluate the shrinkage during holographic recording in an acrylamide photopolymer developed at the Centre for Industrial and Engineering Optics [1] using holographic interferometry, a non destructive technique that measures small static or dynamic changes occurring in an object [2]. Real-time holographic interferometry is a dynamic method by which deformations, including photoinduced dimensional changes in a material can be monitored during the entire experiment [3]. Shrinkage in photopolymer layers can be determined by real time capture of holographic interferograms during holographic recording. The interferograms are produced by interference between a light wave, traversing or reflected from the photopolymer surface, recorded in a separate hologram before photopolymerisation begins and a wave traversing or reflected from the photopolymer surface during the photopolymerisation process which is insensitive to the hologram recording light. A Virtual instrument (VI) developed in LabVIEW (Version 7.1) was used to capture interferograms using a CCD camera at regular intervals. We can determine the optical path change and hence the shrinkage from the captured fringe patterns.The data was use to determine the conditions of recording and the photopolymer composition for which the shrinkage was minimised.

References:

[1] S.Martin, C.A Feely, and V.Toal, “Holographic recording characteristics of an acrylamide based photopolymer,” Appl. Opt. 36, 5757-5768 (1997)

[2] M.T. Manley, B. Ovryn, L.S. Stern. Evaluation of double-exposure holographic interferometry for biomechanical measurements in vitro. J Orthop Res. 5, 144-9 (1997)

[3] D. Pantelic, L. Blazic, S. Savic-sevic, B. Muric, D. Vasiljevic, B. Panic, I. Belic. Real-time measurment of internal stress of dental tissue using holography. Optics Express. 15, 6823-6830 (2007).

8437-18, Poster Session

GPU-based real-time structure light 3D scanner at 500 fps

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The structured-light method is a well-known 3D shape measurement method that can calculate 3D volume information with projection of multiple structured-light patterns. In this method, 3D volume information can be generated via space encoding from a series of structured-light projection images, and the accuracy in 3D shape measurement is determined by the number of projection patterns. In most cases, 3D shape measurement using multiple structure-light patterns is limited for accurate 3D information acquisition of static scenes because of asynchronicity in the series of structured-light projection images; this asynchronicity becomes remarkably serious when standard videos (NTSC 30 fps / PAL 25 fps) are used for 3D measurement. On the other hand, high-speed real-time vision systems operating at hundreds of frames per second or more have been recently developed, and these have made it possible to verify the performance of various algorithms at a high frame rate. If we can implement the structured-light method on the high-speed vision system and reduce the time intervals of each projection from a high-speed projector, the structured-light method can be also applied to high-speed moving 3D objects and arbitrary 3D scenes, because the asynchronicity in a series of structured light patterns are remarkably reduced.

In this study, we develop a real-time structure light three-dimensional (3D) scanner that can output a 3D video of 512 x 512 pixels at a high frame rate of 500 fps using a GPU-based high-speed vision system synchronized with a high-speed DLP projector. In our developed 3D scanner, the high-speed projector projects eight pairs of positive and negative image patterns with 8-bit gray code on the measurement objects at 1000 fps. Synchronized with the high-speed vision platform, IDP Express, these images are simultaneously captured at 1000 fps and they are processed for 3D image generation in real time. These multiple structure light patterns are used for space encoding to generate 3D volume information of the measurement objects and the process for space encoding is extremely accelerated to output a 3D image of 512 x 512 pixels at intervals of 2ms by introducing parallel pixel processing on a GPU board of NVDIA Tesla 1060. In addition with such real-time 3D video recording function at 500 fps, our developed 3D scanner can also implement various types of 3D volume processing in real time at a high frame rate. By utilizing this function, our developed 3D scanner can work as an intelligent high-speed 3D video logging system for long-term monitoring of high-speed phenomena in 3D space. This is possible because of real-time 3D volume processing and high-frame-rate 3D video recording. In order to demonstrate the effectiveness of our developed 3D scanner, several experiments are performed for high-speed moving 3D objects that undergo sudden 3D shape deformation; (1) waving surface of whitened water, (2) human hand whose fingers move quickly, which are too fast for the human eye to observe their 3D shape deformation in detail.

8437-19, Poster Session

FPGA-based computer vision for laser materials processing

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To overcome the lack of spatial resolution in closed loop control,

this paper explains how real-time computer vision improves existing processes and may even enable new laser processes. An example machine vision algorithm is presented which measures kinematic properties of the process zone in real time. The system is based on a framegrabber with on-board FPGA. The calculated measurand is digitally transferred to a D/A-converter which enables the end-user to directly control e.g. the laser power. Such signals provide reliable information of the process state by recovering the influences which cause the process to leave its stable state.

8437-21, Poster Session

Invariant methods for real-time object recognition and image understanding

P. F. Stiller, Texas A&M Univ. (United States)

In this paper we discuss certain recently developed invariant geometric techniques that can be used to fast object recognition or fast image understanding. The results make use of techniques in algebraic geometry that relate the geometric invariants of a feature set in 3D to similar invariants in 2D or 1D. The methods apply equally well to optical images or radar images. In addition to the "object/image" equations relating the invariants, we will discuss certain invariant metrics and show why they provide a more natural and robust test for matching object features to image features. We hope to demonstrate the real-time nature of these methods with an actual application run during the talk. Additional aspects of the work as it applies to shape reconstruction and shape statistics will be explored.

8437-22, Poster Session

Selection of bilevel image compression methods for reduction of communication energy in wireless visual sensor networks

K. Khursheed, M. Imran, N. Ahmad, M. O'Nils, Mid Sweden Univ. (Sweden)

Wireless Visual Sensor Network (WVSN) is an emerging field which combines image sensor, on board computation unit, communication component and energy source. Compared to the traditional wireless sensor network, which operates on one dimensional data, such as temperature, pressure values etc., WVSN operates on two dimensional data (images) which requires higher processing power and communication bandwidth. Normally, WVSNs are deployed in areas where installation of wired solutions is not feasible. The energy budget in these networks is limited to the batteries, because of the wireless nature of the application. Due to the limited availability of energy, the processing at Visual Sensor Nodes (VSN) and communication from VSN to server should consume as low energy as possible. Transmission of raw images wirelessly consumes a lot of energy and requires higher communication bandwidth. Data compression methods reduce data efficiently and hence will be effective in reducing communication cost in WVSN. In this paper, we have compared the compression ratio and complexity of six well known bi-level image compression methods. The focus is to determine the compression algorithms which can efficiently compress bi-level images and their computational complexity is suitable for computational platform used in WVSNs. These results can be used as a road map for selection of compression methods for different sets of constraints in Wireless Visual Sensor Networks.

8437-23, Poster Session

Real-time implementation of a color video processing to contrast enhancement using a DSP DaVinci

A. J. Rosales-Silva, V. Ponomaryov, F. Gallegos, M. Dehesa, Instituto Politécnico Nacional (Mexico)

Algorithm design capable of a video color contrast enhancement in real time using a digital image processor basing our proposal in a reference framework designed by Texas Instruments.

Using the advantages of a Digital Video Processor manufactured by Texas Instruments and the necessity to time optimization in delivering data to other applications, we propose to use a TMS320DM6437 board; this board is the responsible to obtain video image samples to be processed in real time and the responsible to deliver video enhanced to be displayed in a monitor. The usefulness of this kind of algorithms is in visual inspection and automated processes fields among others.

Methodology is related in a histogram equalization proposal used to obtain an image with a uniform distribution. This is that there exists the same number of pixels for each color level of a histogram of a color image.

In fact focus of this work is related to optimize hardware resources in color video processing.

8437-24, Poster Session

Movement detection using an order statistics algorithm

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The presented work addresses the development and implementation of a real-time method for detecting movement of people in video sequences obtained from a static camera, motion detection is a fundamental step for video-surveillance systems, the primary goal of motion detection in our project is the detection of human movement, eliminating the "ghost" movements caused by changes in illumination, background movement and shadows. To achieve the project objectives, we proposed the use of Median Absolute Deviation(MAD), which in the digital image processing reveals the color homogeneity of the image , or levels of intensity in the grayscale images as in our case, so we take advantage of this ability to analysis the local variation of two co-registered frames. Each frame is partioned into 8x8 pixels sub-matrices to calculate the MAD and subtract the corresponding sub-matrices in the adjacent frames. We are currently carrying out a pre-processing of the frames that would reduce ghost movements, at the same time testing thresholding methods to eliminate these same ghosts movements along with trivial movements and thus increase the effectiveness of the algorithm.

8437-25, Poster Session

Real-time FPGA implementation of recursive wavelet transform

C. Patlolla, V. Gopalakrishna, N. Kehtarnavaz, The Univ. of Texas at Dallas (United States); M. Carlsohn, Computer Vision and Image Communication (Germany)

This paper presents the FPGA implementation of recursive wavelet packet transform to achieve a real-time outcome for signal and image processing applications.

To address the computational complexity of the wavelet packet transform of a moving window with a large amount of overlap between consecutive windows, the recursive computation approach was introduced in [1].

In this work, the FPGA implementation of the approach in [1] is reported

using the LabVIEW FPGA module. This programming approach is graphical and requires no knowledge of relatively complex hardware description languages. A number of optimization steps including both filter and wavelet stage pipelining are taken in order to achieve a real-time throughput. The devised FPGA implementation has lead to running a 5-stage wavelet packet transform in real-time with the maximum amount of overlap between consecutive windows.

In comparison, it is shown that the use of the non-recursive or classical wavelet packet transform does not lead to a real-time throughput.

[1] N. Kehtarnavaz, V. Gopalakrishna, and P. Loizou, Recursive Computation of Discrete Wavelet Transform, Chapter 7 in LabVIEW: A Developer's Guide to Real World Integration, CRC Press, 2011.

8437-26, Poster Session

High throughput rendering of optically acquired holograms

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We report an experimental demonstration of an image acquisition scheme designed to perform high speed image reconstruction and display from holographic measurements on a sensor array. High throughput acquisition, numerical reconstruction and display of holograms is achieved with an imaging chain involving a high-speed complementary metal-oxide-semiconductor camera, a high-bandwidth framegrabber and a graphics processing unit (GPU). Our claims are validated by real-time screening of vibration amplitudes in a wide-field, non-contact vibrometry experiment at up to 0.5 Giga pixels per second.

Vibrometric imaging is based on the laser Doppler method, the most common optical interferometry technique used for non-contact measurements of mechanical vibrations. Though highly effective for single-point vibration analysis, this technique is much less adapted to wide-field imaging. It was shown that homodyne and heterodyne holographic recordings enabled reliable measurements of mechanical vibrations, but none of them allowed real-time monitoring, which is an essential feature. Matching the display rate of optically-measured Megapixel digital holograms with real-time imaging standards is demanding in terms of computational power.

We developed holographic rendering algorithms based on parallel computations on GPUs, which were previously shown to increase image rendering throughput with respect to Central processing unit (CPU) computations for optically-acquired, and computer-generated holograms. In our case, GPU processing of the image reconstruction and display algorithm was elaborated with NVIDIA's Compute Unified Device Architecture (CUDA) software. Holographic reconstruction and display with 3 fast Fourier transform calculations per recorded frame is demonstrated. It covers the processing throughput needs of three main holographic reconstruction approaches : the convolution, angular spectrum, and Fresnel transform methods.

8437-27, Poster Session

Real-time visual communication to aid disaster recovery in a multi-segment hybrid wireless networking system

T. Al Hadhrami, Q. Wang, C. Grecos, Univ. of the West of Scotland (United Kingdom)

When natural disasters or other large scale incidents occur, obtaining accurate and timely information on the developing situation is vital to effective disaster recovery operations. High-quality video streams and high-resolution still images, if available in real time, would provide an invaluable source of current situation reports to the incident management team. Meanwhile, a disaster often causes significant damage to the communications infrastructure. Therefore, another essential requirement for disaster management is the ability to rapidly deploy a flexible incident area communication network. Such a network would facilitate the transmission of real-time video streams and still images from the disrupted area to remote command and control locations.

In this paper, we propose a comprehensive end-to-end video/image transmission system between an incident area and a remote control centre and experimentally investigate its performance. We design a hybrid multi-segment communication network that seamlessly integrates terrestrial wireless mesh networks (WMNs), distributed wireless visual sensor networks, an airborne platform with video camera balloons, and a Digital Video Broadcasting- Satellite (DVB-S) system. WMNs are multi-hop infrastructure-independent wireless networks with quick deployment, self-healing, self-organisation and self-configuration features, which make WMNs a promising network technology for instant and reliable visual communications during emergency situations. The on-site rescue team members are mesh clients that capture visual information on the move. For visual content acquisition and transmission in more hostile, dangerous areas, a spatially distributed autonomous network of visual sensors is employed to monitor physical and environment conditions. Visual content of larger scale is fed into the system through video camera balloons, which offer obstacle-free bird-eye visions from the air. Video balloon nodes can also roam across and interact with the various communication segments in the system. Finally, the DVB-S system requires only moderate terrestrial infrastructure to set up and utilises satellites (usually intact after terrestrial disasters) to cover a wide area to bridge the incident area and the remote control centre.

By carefully integrating all of these rapidly deployable, interworking and collaborative networking technologies, we can fully exploit the joint benefits provided by WMNs, WSNs, balloon camera networks and DVB-S for real-time video streaming and image delivery in emergency situations among the disaster hit area, the remote control centre and the rescue teams in the field. We implement the whole proposed system in a proven simulator. Through extensive simulations, we numerically evaluate the real-time visual communication performance of this integrated system. We further present an in-depth analysis of the proposed solutions and potential approaches towards supporting high-quality visual communications in such a demanding context.

8437-28, Poster Session

Real-time video streaming in mobile cloud over heterogeneous wireless networks

S. Abdallah-Saleh, Q. Wang, C. Grecos, Univ. of the West of Scotland (United Kingdom)

Recently, the concept of Mobile Cloud Computing has been proposed to offload the resource requirements in computational capabilities, storage and security from mobile devices into the cloud. Internet video applications such as real-time streaming are expected to be ubiquitously deployed and supported over the cloud for mobile users, who typically encounter a range of wireless networks of diverse radio access technologies during their roaming. However, real-time video streaming for mobile cloud users across heterogeneous wireless networks presents multiple challenges. The network-layer quality of service (QoS) provision to support high-quality mobile video delivery in this demanding scenario remains an open research question, and this in turn affects the application-level visual quality and impedes mobile users' perceived quality of experience (QoE).

In this paper, we devise a framework to support real-time video streaming in this new mobile video networking paradigm and evaluate the performance of the proposed framework empirically through a lab-based yet realistic testing platform. The study explores different approaches to leveraging the benefits of Mobile Cloud Computing to support video streaming whilst circumventing the issues caused by this paradigm shift. One particular issue we focus on is the effect of users' mobility on the QoS (and thus the QoE) of video streaming over the cloud. We design and implement a hybrid platform comprising of a testbed and an emulator, on which our concept of mobile cloud computing, video streaming and heterogeneous wireless networks are implemented and integrated to allow the testing of our framework. As representative heterogeneous wireless networks, the popular Wi-Fi and WiMAX networks are incorporated in order to evaluate effects of handovers between these different radio access technologies. The H.264/AVC standard is employed for real-time video streaming from a server to mobile users (client nodes) in the networks. Mobility support is introduced to enable continuous streaming experience for a mobile user across the heterogeneous wireless network. Real-time video stream packets are captured for analytical purposes on the mobile user node. Experimental results are obtained and analysed. Future work is identified towards further improvement of the current design and implementation.

With this new mobile video networking concept and paradigm implemented and evaluated, results and observations obtained from this study would form the basis of a more in-depth, comprehensive understanding of various challenges and opportunities in supporting high-quality real-time video streaming in mobile cloud over heterogeneous wireless networks.

8437-29, Poster Session

Real-time 3D object topography using the Talbot effect

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The optical techniques for 3D shape measurement play an increasingly important role for various applications, such as quality control, archeology, virtual reality, industrial inspection, reverse engineering, etc. Optical topography is simple, inexpensive and nondestructive procedure and has no contact with the object. Some common techniques are stereo-vision, laser scanning, structured light, phase shifting, interferometry, Moire and so on. We are using fringe projection in a modern way. The main idea of our proposed method is using real sinusoidal pattern and Talbot effect Therefore less noise, more simple analysis and faster processes will be eventuated.

A collimated (parallel) laser beam is projected on a grid and produce self-images of the grid in different distances. In order to remove high frequency orders of Talbot, we used a lens as Fourier transformer. A 2-hole plane used at its focus for selection of +1 and -1 components and by using an inverse Fourier transform, we produced complete sinusoidal pattern. This pattern is projected on object surface and deformed pattern of the projected beams used for analyzing three dimensional profile of the reference object. This method has the lowest-order aberration, highest contrast ratio and most complete sinusoidal pattern.

To obtain the phase map and build a model we used two-dimensional Fourier transform and then phase unwrapping algorithms. The advantage of analyzing by two-dimensional Fourier transform is producing three dimensional profile using only one frame in real time domain. Although simple Fourier transform technique is used in real-time analysis, our proposed methods speed is acceptable. We compared our method vs classical methods which uses video projector. As a result we observed our model is more accurate than common methods and perform as a real time procedure because of avoiding complicated methods and time-consuming calculations.

8437-30, Poster Session

Cost optimization of a sky surveillance visual sensor network

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A Visual Sensor Network (VSN) is a network of spatially distributed cameras. The primary difference between VSN and other type of sensor network is the nature and volume of information. A VSN generally consists of cameras, communication, storage and central computer, where image data from multiple cameras is processed and fused. In this paper, we use optimization techniques to reduce the cost as derived by a model of a VSN to track large birds, such as Golden Eagle, in the sky. The core idea is to divide a given monitoring range of altitudes into a number of sub-ranges of altitudes. The sub-ranges of altitudes are monitored by individual VSNs, VSN1 monitors lower range, VSN2 monitors next higher and so on, such that a minimum cost is used to monitor a given area. The VSNs may use similar or different types of cameras but different optical components, thus, forming a heterogeneous network. We have calculated the cost required to cover a given area by considering an altitudes range as single element and also by dividing it into sub-ranges. To cover a given area with given altitudes range, with a single VSN requires 694 camera nodes in comparison to dividing this range into sub-ranges of altitudes, which requires only 96 nodes, which is 86% reduction in the cost.

8437-31, Poster Session

Fast repurposing of high-resolution stereo video content for mobile use

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3D video content is captured and created mainly in high resolution targeting big cinema or home TV screens. For 3D mobile devices, equipped with small-size auto-stereoscopic displays, such content has to be properly repurposed, preferably in real-time. The repurposing requires not only spatial resizing but also properly maintaining the output stereo disparity, as it should deliver realistic, pleasant and harmless 3D perception.

In this paper, we propose an approach to adapt the disparity range of the source video to the comfort disparity zone of the target display. To achieve this, we adapt the scale and the aspect ratio of the source video. We aim at maximizing the disparity range of the retargeted content within the comfort zone, and minimizing the letterboxing of the cropped content.

The proposed algorithm consists of five stages. First, we analyse the display profile, which characterizes what 3D content can be comfortably observed in the target display. Then, we perform fast disparity analysis of the input stereoscopic content. Instead of returning the dense disparity map, it returns an estimate of the disparity statistics (min, max, mean, variance) per frame. Additionally, we detect scene cuts, where sharp transitions in disparities occur. Based on the estimated input, and desired output disparity ranges, we derive the optimal cropping parameters and scale of the cropping window, which would yield the targeted disparity range and minimize the area of cropped and letterboxed content. Once the rescaling and cropping parameters are known, we perform resampling procedure using spline-based and perceptually optimized resampling (anti-aliasing) kernels, which have also a very efficient computational structure. Perceptual optimization is achieved through adjusting the cut-off frequency of the anti-aliasing filter with the throughput of the target display.

8437-32, Poster Session

Multi-resolution model-based traffic sign detection and tracking

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Video-based Advanced Driver Assistance Systems (ADAS) are one of the most appealing fields within Computer Vision applications. Traffic sign detection appears as one of the most attractive topics of research related to ADAS. This kind of system is meant to provide information about the road signs and alert the driver about possible hazards. One of the challenges of this type of systems is the requirement of having high reliability working in real time operation conditions.

The complex nature of road environments makes it very difficult to develop computationally efficient computer vision algorithms. In such complex scenarios, what is highly intuitive for us as humans, may be not easily tractable mathematically, requiring often slow and complex algorithms applied to a huge amount of data, commonly corrupted by noise, coming from the camera.

In this paper we propose an innovative approach to deal with the problem of traffic sign detection using a computer vision algorithm and taking into account real-time operation constraints, trying to establish intelligent strategies to simplify as much as possible the algorithm complexity and to speed up the process.

In our proposal, a set o hypotheses (potential Traffic Signs, TSs) are generated through a pixel-wise color-based segmentation strategy followed by a standard connected-components analysis phase, where spatial characteristics of TSs are taken into account. Finally, temporal information is considered through a tracking stage. Color-based segmentation is carried out through a Bayes classification strategy, where Mixture of Gaussians distributions are used to accurately model the TSs colors in HSV space. For each candidate TS, a fast region analysis is carried out considering spatial TS characteristics (size, pictogram size and aspect ratio) and their expected temporal evolution. Temporal analysis is based on a Kalman-based tracking scheme that helps not only to remove outliers but also to improve further segmentation results.

Efficiency is achieved two-fold. First, a multiresolution strategy is adopted for segmentation: global operations are applied only to low resolution images, while the resolution is increased to the maximum only in those areas where candidates have been detected previously. To perform this task we rely on the tracking predictions, which let us locate the candidates in future frames according to its expected temporal evolution. Full resolution processing is then restricted to image areas where traffic signs are predicted to be located. Color and region models are also quantized at different levels of granularity using look-up-tables in order to alleviate computational requirements. Second, we take advantage of the expected spacing between traffic signs. Namely, the tracking of objects of interest allows to generate inhibition areas, which are those ones where no new traffic signs are expected to appear due to the existence of a TS in the neighborhood.

8437-34, Poster Session

Robust point and small target detection algorithm based on selective double structuring element morphology

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A novel simple and robust algorithm for detection of point and small targets in visible and infra-red image sequences is presented in this letter. The proposed detection algorithm is based on the novel selective double structuring element top-hat transform (Sel-DSTHT) and maximum correlation criterion. A switching logic based on variance of the input image is used to apply an additional rule to modify the filtered image for highly cluttered images. Results demonstrate high probability of detection and low false alarms even for highly clouded scenario. Reduced number of operation leads to suitability for real time implementation.

8437-35, Poster Session

Imaging enhanced with StillI

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In this paper we present StillI, new software from Flexible Optical BV which extends the capabilities of modern imaging systems. It offers almost real time image enhancement through turbulent and wavy media, where the image features are unresolved due to loss of contrast, blur, vibrations and image wander. As an aid in increasing the information content in the resulting image sequence, the software allows applying an arbitrary combination of several image processing methods in real time, including image stabilization, object tracking, frame integration, contrast enhancement and multi-frame deconvolution. The software works with live video sequences; it can be used both for astronomical and terrestrial observations.

In astronomy, stabilization allows compensating for the tracking error, vibrations and turbulence-induced image wander. Frame integration allows visualizing weak astronomical objects, such as galaxies, moons and star clusters. It is especially efficient when used in combination with stabilization on brighter objects (stars and planets) located within the field of view. Multi-frame deconvolution can be applied to compensate the image blur which occurs due to the atmospheric turbulence. We use an iterative procedure to reconstruct individual point-spread functions (PSF) in a series of short-exposure images of the same object; further, we apply Wiener filtering to estimate the undistorted object. We show that the efficiency of this procedure can be further increased by rejecting unsharp frames from the initial sequence based on sharpness functional.

In terrestrial imaging, compensation of the turbulence effects is required for objects observed at ~100 m to ~10 km distances, depending on terrain and weather conditions. We show that the image quality improvement can be achieved for the image blur observed in isoplanatic case and image warp in anisoplanatic one. Examples are presented showing how the software can be applied for removing image distortions when observing through wavy water surface.

8437-36, Poster Session

Real-time machine vision system using FPGA and soft-core processor

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This paper presents a machine vision system for real-time image component labelling, feature extraction, as well as angle and distance measurement of a camera from the reference points in the environment. Image component labelling and features extraction modules were developed in hardware description language, VHDL. The feature extracted from these hardware modules were fed to a soft-core processor “MicroBlaze”, which performs the distance and angle measurement from six reference points. CMOS imaging sensor, MT9V032 operating at maximum clock frequency of 27MHz, used in experiments produce images at the rate of 75 frames per second. Image component labeling and feature extraction modules are running in parallel and have latency of 13ms at a clock frequency of 27MHz. MicroBlaze was operated at 100MHz and connected to the hardware module through Fast Simplex Link (FSL). The latency of MicroBlaze for calculating distance and angle of camera from reference point is 2ms. In this paper we present the performance analysis, device utilization and power consumption issues for the designed system. The designed system has high frame speed and low latency. The power consumption of the system is much lower than commercially available smart camera solutions.

8437-01, Session 1

GePaRDT, a framework for massively parallel processing of dataflow graphs

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The trend towards computers with multiple processing units keeps going with no end in sight. Modern consumer computers come with 2 - 6 processing units. Programming methods have been unable to keep up with this fast development. Existing options for an effective usage of multiple processing units are sophisticated so they are only used by programming experts.

There exists a graphical model that describes a specific type of data processing: the dataflow graph. Graphs are well known models that represent a set of nodes where pairs of them are linked together by edges. The nodes in a dataflow graph depict independent tasks where data is processed, edges describe the order of them respectively how the data flows from one processing task to another.

Here we present a framework that uses this model for parallel processing: the Generic Parallel Rapid Development Toolkit, GePaRDT.

Nodes are assigned to one or more threads such that complex tasks can use more than one thread at the same time. The complementary case where multiple nodes correspond to one single thread is also feasable and simple to configure in GePaRDT. The number of threads does not necessarily correspond to the number of CPU cores. We show that a slight oversubscription of the CPU gives the best results in terms of data throughput. The correspondence between nodes and threads is therefore be simply configured by a user. An automatic assignment was omitted here since this poses a NP-complete optimization problem.

The edges which can be considered as frontiers between tasks respectively processing units are implemented using lock-free MPMC queues for an optimal inter-thread communication. The implementation is done in C# (.NET 4.0 framework) using the Task Parallel Library (TPL).

Since GePaRDT has a very simple API the user does not need an in depth understanding of parallel processing. We are successfully using GePaRDT in a project (funded by The Commission for Technology and Innovation CTI in Switzerland) to measure distances in 20nm resolution with an interferometry approach using a fiber probe. Here we are processing more than 100 images in VGA resolution per second. This is done on a Intel Quad-Core CPU with enabled HyperThreading (8 virtual cores). A similar implementation using standard programming methods was able to process about 9 images per second.

8437-02, Session 1

Image segmentation in wavelet transform space implemented on DSP

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Within the image processing, there is the segmentation process that involves partitioning an image into a set of homogeneous and meaningful regions, such that the pixels in each partitioned region possess an identical set of properties or attributes. The result of segmentation is a number of homogeneous regions, each having a unique label. Image segmentation is often considered to be the most important task in computer vision. However, the segmentation in images is a challenging task due to several reasons: irregular and dispersive lesion borders, low contrast, artifacts in the image and variety of colors within the interest region.

In this work, we propose novel framework that consists in employing the feature extraction in WT space before the segmentation process. The main difference of novel approach in comparison with other algorithms presented in literature is in usage the information from three-color channels in WT space gathering the color channels via a nearest neighbor interpolation (NNI). Novel algorithms apply the procedure that consists in separation of a digital color image in R, G and B channels, where each a color channel is decomposed into four sub-bands where the sub-bands LH, HL and HH represent the finest scale wavelet coefficients, while the sub-band LL corresponds to coarse level coefficients, used in the DWT. This approach in segmentation has generated several novel frameworks: WK-Means, W-FCM, W-CPSFCM), that we compare with other algorithms such as AT, SRM, K-Means, and FCM. The measures (Sensitivity and Specificity), the Receiver Operating Characteristic (ROC) analysis, and quantitative summary measure (AUC) were applied in the performance characterization of novel and existed segmentation algorithms. Numerous results of the simulation experiments with synthetic, medical, and satellite images have confirmed better performance of novel framework comparing them with existed techniques. Additionally, we present the results of implementation of the better segmentation algorithms in real time mode on DSP TMS320DM642 of TI, using Matlab 2009a TM, TC6 software, CCS, IDE with the Real-Time Workshop software, and Simulink.

8437-03, Session 1

A contourlet transform based algorithm for real-time video encoding

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In recent years, real-time video communication over the internet has been widely utilized for applications like video conferencing. Streaming live video over heterogeneous IP networks, including wireless networks, requires video coding algorithms that can support various levels of quality in order to adapt to the network end-to-end bandwidth and transmitter/receiver resources. In this work, a scalable video coding and compression algorithm based on the Contourlet Transform is proposed. The discrete contourlet transform is utilized for the multiscale and directional representation of each video frame. Its ability to efficiently approximate smooth contours makes it suitable for natural images. Multiscale decomposition allows the algorithm to support multiple levels of detail without re-encoding the video frames, by just dropping the encoded information referring to higher resolution than needed. Compression is achieved by means of lossy and lossless methods, as well as variable bit rate encoding schemes. In the first compression stage, only the most significant contourlet coefficients are retained, subsequently stored in an arithmetic precision. The coefficients' precision levels are controlled by a user-defined quality parameter, which affects the output's visual quality and compression ratio. The algorithm also takes advantage of the redundancy of high frequency content across the chromatic channels to further reduce the output size. The directional subbands obtained by applying the contourlet transform are very sparse, leading to the second compression stage that consists of run-length encoding. After the compression stage a low computational complexity variable bit rate coding scheme is applied in order to increase the compression ratio while introducing minimal delay. Due to the transformation utilized, the output does not suffer from blocking artifacts that occur with many widely adopted compression algorithms. Another highly advantageous characteristic of the algorithm is the suppression of noise induced by low-quality sensors usually encountered in web-cameras, due to the manipulation of the transform coefficients at the compression stage. The proposed algorithm is designed to introduce minimal coding delay, thus achieving real-time performance. This is achieved by utilizing the vast computational capabilities of modern GPUs through the NVIDIA CUDA architecture, providing satisfactory encoding and decoding times at relatively low cost. These characteristics make this method suitable for applications like video-conferencing that demand real-time performance, along with the highest visual quality possible for each user. Through the presented performance and quality evaluation of the algorithm, experimental results show that the proposed algorithm achieves better or comparable visual quality relative to other compression and encoding methods tested, while maintaining a satisfactory compression ratio. Especially at low bitrates, it provides more human-eye friendly images compared to algorithms utilizing block-based coding, like the MPEG family, as it introduces fuzziness and blurring instead of artificial block artifacts.

8437-04, Session 1

Capturing reading patterns through a real-time smart camera iris tracking system

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A real-time iris detection and tracking algorithm has been implemented in a NI smart camera using LabVIEW graphical programming tools. The program detects the eye and finds the center of the iris, which is recorded and stored in Cartesian coordinates. In subsequent video frames, the location of the center of the iris corresponding to the previously detected eye is computed and recorded for a desired period of time, creating a list of coordinates representing the moving location of the iris center across image frames. The live video frames are spaced temporally equally apart which can then be used as a reference during the analysis of the data.

We present an application for the developed smart camera iris tracking system that involves the assessment of reading patterns of accomplished and aspiring readers. The purpose of the study is to identify differences in reading patterns of readers at various levels to eventually determine successful reading strategies. Through this research, the answers to three questions are sought: 1) Do traditional notions of directionality, that is reading left to right, apply when reading digital print? 2) What textual aspects do readers focus on first when viewing a page? 3) How does reading digital texts compare to reading traditional printed texts?

The readers are sat in front of a computer screen with a fixed camera directed at the reader's face. The smart camera field of view corresponding to the computer screen size is calibrated before data capture by asking the reader to look at two diagonal corners of the screen and recording these calibration points. The readers are then asked to read the text on the computer screen with preselected Websites and Web content that could include graphics. The iris path is captured in real-time. The reading patterns are examined by analyzing the path of the iris movement. The iris center data points are sequentially connected representing the iris track on a 2D grid. The reading patterns are investigated for the speed of reading determined throughout the analysis of distances between subsequent data points, how the reader browses through the text and Web by analyzing the iris path tracked, and finally the length and location of gaze on the screen by quantifying directional variations and persistent coordinates in the iris track.

In this paper, the iris tracking system and algorithms, the application of the system to real-time capture of reading patterns, and analysis of 2D iris track are presented with results and recommendations.

8437-05, Session 1

Video-based realtime IMU-camera calibration for robot navigation

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This paper introduces a new method for fast calibration of inertial measurement units (IMU) with cameras being rigidly coupled. That is, the relative rotation and translation between the IMU and the camera is estimated, allowing for the transfer of IMU data to the cameras coordinate frame. Moreover, the IMUs nuisance parameters (biases and scales) and the horizontal alignment of the initial camera frame are determined. Since an iterated Kalman Filter is used for estimation, information on the estimations precision is also available. Such calibrations are crucial for IMU-aided visual robot navigation, i.e. SLAM, since wrong calibrations cause biases and drifts in the estimated position and orientation. Because the estimation is performed in real time, the calibration can be done using a freehand movement and the estimated parameters can be validated just in time. This provides the opportunity of optimizing the used trajectory online, increasing the quality and minimizing the time effort for calibration. Except for a marker pattern, used for visual tracking, no additional hardware is required.

As will be shown, the system is capable of estimating the calibration within a short period of time. Depending on the requested precision trajectories of 30 seconds to a few minutes are sufficient. This allows for calibrating the system at startup. By this, deviations in the calibration due to transport and storage can be compensated. The estimation quality and consistency are evaluated in dependency of the traveled trajectories and the amount of IMU-camera displacement and rotation misalignment. It is analyzed, how different types of visual markers, i.e. 2- and 3-dimensional patterns, effect the estimation. Moreover, the method is applied to mono and stereo vision systems, providing information on the applicability to robot systems. The algorithm is implemented using a modular software framework, such that it can be adopted to altered conditions easily.

8437-06, Session 2

GPU acceleration towards real-time image reconstruction in 3D tomographic diffractive microscopy

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Phase microscopy techniques regained interest since they allow for the observation of unprepared specimens with excellent temporal resolution. Tomographic diffractive microscopy is an extension of holographic microscopy and allows for 3D observations with a finer resolution than incoherent light microscopes. Specimens are imaged in quantifying the distribution of their optical indexes : a series of 2D interferograms progressively fills the range of frequencies of the specimen in Fourier space, a 3D FFT yielding a resulting spatial image [1].

Consequently, acquisition then reconstruction are mandatory to produce an image, which can prelude real-time control of the observed specimen. The MIPS Laboratory has built a tomography diffractive microscope with an unsurpassed resolution of 130 nm [2] at the cost of a low imaging speed. It is now able to acquire the 1000 interferograms we need for proper imaging within one minute, and a high-end PC (Intel 2600K + 16 GB DDR3) can run space/time optimized reconstruction in 50 seconds. We intend to design a faster system, able to display living specimens in 3D with an update rate of a few seconds.

The reconstruction program mostly relies on the multithreaded FFTw. It takes 20 seconds to merge all the 2D interferograms at once into a single volume using forward 2D FFTs, 8 seconds to produce an image via a 3D backward FFT, the rest being spend in disk I/O due to the separation with the acquisition program. Both programs were rewritten in a producer / consumer scheme, sharing interferograms via system memory: this allows for 5 updates of the displayed 3D volume (VTK) during the acquisition, progressively showing more details in a coarse to fine manner. The bottleneck clearly relies on the 3D backward FFT of the 512^3 volume.

To achieve faster update, we cannot expect much from the CPU side according to the Intel/AMD roadmaps: core frequency evolves slowly, and the FFTw algorithm shows logarithmic performance increase over number of cores involved (from 4 to seven in our case) due to synchronization overhead. Thus, we considered GPU computing, namely the CUDA 4 Toolkit and the cuFFT library, which offer a scalable and auto-organized computing grid counting hundreds of processing cores. An entry-level GPU (GTX 560Ti, 336 cores) managed to compute a 3D FFT in 4 seconds instead of 8 (PCIe transfert included), enabling a visualization update in 5 seconds instead of 10. Better mainstream GPUs (580 series, 512 cores) are supposed to yield updates in 3 seconds, and we now intend to acquire a high-end Tesla card to get closer from 1 second.

Although software architecture optimizations are of paramount importance for allowing progressive image reconstruction and vizualisation, GPU processing speed is determinant for reaching proper update rates, opening opportunities for 4D imaging of living specimens or over-time evolving processes like cristallization.

[1] Optics Communications, 1, 153-156,(1969)

[2] Optics Letters, 34(1), 79-81, (2009).

8437-07, Session 2

A flexible software architecture for scalable real-time image and video processing applications

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The design and implementation of real-time image and video processing applications are complex tasks that require much effort. Also, due to the recent trends in the hardware platform, such as the steady increase in computing power based on parallelism and the improved resolution and image acquisition rate of low cost imaging devices, applications require even more skilled architects. Designing, developing, and tuning the applications to meet real-time constraints require expertise knowledge in different areas, such as parallelism, computer architecture, or image processing. Many frameworks and libraries have been proposed or commercialized. However, in general they lack flexibility because they are normally oriented towards particular type of applications, or they impose specific data processing models such as the pipeline. Other issues include large memory footprint, difficulty to reuse, or inefficient execution on multicore processors. This paper presents a novel software architecture for real-time image and video processing applications which addresses these issues. The architecture is divided into three layers: the platform abstraction layer, the messaging layer, and the application layer. The platform abstraction layer provides a high level application programming interface for the rest of the architecture. This layer simplifies the development of the architecture and makes it operating system independent. The messaging layer provides a messaging passing interface based on a dynamic publish/subscribe pattern. A topic-based filtering in which messages are published to topics is used to route the messages from the publishers to the subscribers interested in that particular type of messages. Messages can be as flexible as possible. Also, different mechanisms are used to avoid expensive data copying and policies are provided to efficiently execute publishers and subscribers in parallel. The application layer is application dependent. However, we provide a repository of reusable application modules designed for real-time image and video processing applications. Among these modules, acquisition, visualization, communication, user interface and data processing modules are included. These modules take advantage of the power of other well-known libraries such as OpenCV, Intel IPP, or CUDA. Finally, we summarize some of the prototypes and applications in which we are working on, and discuss directions for future.

8437-08, Session 2

Dense real-time stereo matching using memory efficient semi-global-matching based on FPGAs

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This paper presents a stereo image matching system that takes advantage of a global image matching method. The system is designed to provide depth information for mobile robotic applications. Typical tasks of the proposed system are to assist in obstacle avoidance, SLAM and path planning of mobile robots, that pose strong requirements on the size, energy consumption, reliability, frame rate and quality of the calculated depth map. Current available systems either rely on active sensors or on local stereo-image matching algorithms. The first are only suitable in controlled environments while the second suffer from low quality depth-maps. Top ranking quality results are only achieved by an iterative approach using global image matching and colour segmentation techniques which are computationally demanding and therefore difficult to be executed in real time. Attempts were made to still reach real-time performance with global methods by simplifying the routines but led to degraded depth maps which are at the end almost comparable with local methods. An equally named semi-global algorithm was proposed earlier, that shows both very good image matching results and relatively simple execution at the same time. A memory efficient variant of the Semi-Global Matching algorithm is reviewed and adopted for an implementation based on reconfigurable hardware that is suitable for real-time operations in the field of robotics. It will be shown that the modified version of the efficient Semi-Global matching method is delivering equivalent result compared to the original algorithm based on the Middlebury dataset.

The system has proven to be capable of processing VGA-sized images with a disparity resolution of 64 steps at 33 frames per second based on low cost to mid-range hardware. In case the focus is shifted to a higher image resolution 1024x1024-sized stereo-frames may be processed with the same hardware at 10 fps and the unchanged disparity resolution settings. The implementation is also compared to parallel CPU and GPU variants. The complete design has been implemented within a hardware development framework that is also briefly reviewed. Depending on the available resources, different pre- and post-processing steps may be executed in hardware allowing for an embedded system tailored to a specific application.

8437-09, Session 2

Embedded smart vision system based on CogniMem neural processor: application to person detection

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Nowadays, person detection is more and more necessary in the context of security applications. In this context, several systems have been proposed like single standalone video systems or PC-based solutions. If these systems can reach relative good performances in terms of success of detection, they require however presence of human operator assistance and in general, automatic detection in these systems is not embedded because used image processing algorithms require a lot of calculations which are difficult to implement on hardware.

One solution to improve performances of such systems is to use artificial neural network whose characteristic is to emulate the reasoning of the human brain which can recognize with surprising ease, and in real tim, a pattern from the moment it was learned.

Moreover, neural network is inherently a group of elements with the same behavior, it is a candidate for a parallel architecture.

In this field, the CogniMem chip is a fully parallel silicon neural network: it is a chain of 1024 identical elements (i.e. neurons) addressed in parallel and which have their own “genetic” material to learn and recall patterns without running a single line of code and without synchronizing to any supervising unit. A resulting achievement of this architecture is a constant learning and recognition time regardless of the number of connected neurons.

Using the CogniMem chip connected to an Aptina MT9V024 CMOS sensor (752x488 pixels) and to a Microchip dsPIC33EP microcontroller, we designed a new embedded smart vision system which allows to detect in real time and with a low power consumption (less than 1w), the presence of human persons in natural scenes. Thanks to the neural network characteristics, classification of persons versus no persons (like animal for example) is obtained with a high accuracy (more than 95%).

8437-10, Session 3

Real-time video breakup detection for multiple HD video streams on a single GPU

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An important task in film and video preservation is the quality assessment of the content to be archived or reused out of the archive. This task, if done manually, is a straining and time consuming process, so it is highly recommended to automate this process as far as possible. Furthermore, archives and broadcasters have large amounts of video content (millions of hours) whose visual quality is to be checked. In order to handle this amount of data, algorithms are crucially needed which are able to process not only one, but multiple video streams in real-time on a single computer. In this paper, we show how to port a previously proposed algorithm for detection of severe analog and digital video distortions (termed “video breakup”) efficiently to NVIDIA GPUs of the Fermi Architecture using CUDA. The two measures which build the core of the algorithm - row change measure and edge ratio measure - are parallelized massively in order to take usage of the hundreds of cores of an typical GPU and are modified so that they take advantage of the unique capabilities of the GPU like shared memory and texture memory. Furthermore, for the generation of the row histograms, which are used within the calculation of the row change measure, we employ a novel approach involving multiple sub-histograms which are subsequently merged in order to lessen significantly the runtime penalty one normally has to deal with when calculating histograms on the GPU. Runtime comparisons show that we achieve a speedup factor of roughly 10 - 15 when comparing the GPU implementation with a highly optimized, multi-threaded CPU implementation. Thus our GPU algorithm is able to analyze nine Full HD (1920 x 1080) video streams or 40 standard definition (720 x 576) video streams in real-time on a single inexpensive NVIDIA Geforce GTX 480 GPU. Additionally, we present the AV-Inspector application for video quality analysis and verification, which integrates the proposed video breakup detector along with other video-quality related algorithms (e.g. for measuring the amount of noise in the video) and allows the user to get an assessment of the quality of video and film material in very short time.

8437-11, Session 3

Complexity analysis of vision functions for implementation of wireless smart cameras using system taxonomy

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The large amount of data and limited resources in wireless smart cameras impose challenges when implementing the vision processing algorithms on embedded platforms. Generally, the common challenges include limited memory, processing capability, power consumption, in case of battery operated systems, and bandwidth, in case of wireless systems. The consideration of architectural issues in case of real time embedded vision systems is more important than general purpose computer vision systems. Currently, the researchers in this field are mostly focusing on the development of a particular solution for a particular problem. To implement vision functions on embedded vision systems, the designers first investigate the resource requirements for a design. Failing to do this may result in additional design time and cost to meet the specifications. There is a need to have a model for prediction of the resources required for the development of wireless smart cameras. To the best of our knowledge, there is no such model exists which shows the complexity and memory requirements for different class of wireless smart cameras. To fill this gap, we have used system taxonomy which shows that majority of wireless smart cameras focus on object detection, analysis and recognition. These tasks can be reduced to the vision functions such as image subtraction, segmentation, filtering, transformation, machine learning and post processing tasks such as labeling, feature extraction, recognition, etc. In this paper, we have investigated the computational complexity and memory requirements of different vision functions mentioned in the system taxonomy. The study will help designers to predict the resource requirements for different class of wireless smart cameras in a reduced time and with little efforts. It will be an important step towards the generalization of solutions in wireless smart cameras implemented on embedded systems.

8437-12, Session 3

Benchmarking real-time HEVC streaming

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Work towards the standardisation of High Efficiency Video Coding (HEVC), the next generation video coding scheme, is currently gaining pace. HEVC offers the prospect of a 50% improvement in compression over the current H.264 Advanced Video Coding standard (H.264/AVC) for the same quality. Thus far, work on HEVC has concentrated on improvements to the coding efficiency and has not yet addressed transmission in networks. For now, the HEVC working draft only mandates byte stream compliance with Annex B of H.264/AVC as the means for transport in systems that are not based on the Internet Protocol (IP). For practical networked HEVC applications, a number of essential building blocks have yet to be defined.

In this paper, we design and prototype a real-time HEVC streaming system and empirically evaluate its performance. In particular, we investigate the robustness of the current Test Model under Consideration (TMuC HM4.0) for HEVC to packet loss both in terms of decoder resilience and degradation in perceptual video quality. A Network Abstraction Layer (NAL) unit packetisation and streaming framework for HEVC encoded video streams is designed, implemented and empirically tested in a number of streaming scenarios in IP-based wired and wireless networking environments. The HEVC decoder's error resilience is tested under a comprehensive set of packet loss conditions, and a simple error concealment method for HEVC is used for the current HEVC decoder. We observe that similarly to H.264 encoded streams, the size and the distribution of NAL units within an HEVC stream and the nature of the NAL unit dependencies influence the packetisation and streaming strategies which may be employed for such streams. We further test our prototype with the different HEVC encoding modes (low delay, random access etc.) and study the relationships between HEVC encoding modes, coding unit and slice sizes and the quality of the received video are studied across a wide range of packet loss ratio and network configuration scenarios. Through the use of extensive experimentation, we establish a comprehensive set of benchmarks for HEVC streaming in loss prone network environments.

To the best of our knowledge, this is the first time that such a fully functional streaming system for HEVC, together with the benchmarking evaluation results, has been reported. We hope that this study will open up more timely R&D opportunities in this cutting edge area.

8437-13, Session 3

2000-fps multi-object tracking based on color histogram

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The color histogram is a well-known shape-invariant image feature that can be used for robust target tracking, and various types of color-histogram-based tracking algorithms, e.g., the CAM-SHIFT method, have already been developed to perform target tracking for humans and other moving objects in actual scenes. However, the tracking frame rates of these color tracking applications are limited to the recognition speed of the human eye, because the cameras used in these applications are restricted by video signal formats (e.g., NTSC 30 fps and PAL 25 fps) designed according to the characteristics of the human eye. Recently, high-speed real-time vision systems operating at 1000 fps or more have been developed by implementing image processing algorithms with hardware logic circuits on a dedicated FPGA board, and these have made it possible to verify the performance of various algorithms at a high frame rate. Actually, a real-time target tracking vision system has been developed based on color histogram, which can work at 2000 fps by hardware implementation. However, this system just can tracking one object in an image. On the other hand, a high-speed multi-object extraction system has been developed based on a cell-based labeling algorithm, which can work at 2000 fps by hardware implementation. If we could combine the advantages of these two systems, the frame rate of a

robust multi-object color tracking vision system, which is currently limited to 30 fps, will be improved by at least 30 times.

In this study, we develop a high-speed multi-object tracking vision system that can be applied to 8-bit 512x512 pixels color images at 2000 fps by implementing an improved cell-based labeling algorithm as hardware logic on an FPGA-based high-speed vision platform, IDP-Express. Based on the additivity in calculating moment features and color histograms, the improved cell-based labeling algorithm can extract the size, position, orientation, and color histogram of 256 regions to be tracked in an image using only the hardware implementation of cell-based labeling algorithm with a 16-bins color histogram module. By initially assigned color bins and by calculating the moment features of 256 probability distribution regions as scalar values, which are weighted by the probabilities of 16 color bins in the tracked regions. An improved cell-based labeling algorithm was actually designed to calculate the 0th, 1st, 2nd moment features, and color histogram features for 256 labeled regions by using hardware implementation. By integrating the color histogram extraction circuit module with cell-based labeling circuit module on a user-specific FPGA on IDP Express, we can obtain both the 512x512 pixel input image and the features of 256 labeled regions to a standard memory of a personal computer in real-time at 2000 fps.

Finally, we present several experiment results for showing the efficiency of our high-speed multi-object tracking system: (1) a pattern with many color objects rotating at 16 rps and (2) two human hands moving rapidly at 4 Hz in a room. These results indicate that our color-histogram-based multi-object target tracking system can robustly track high-speed moving objects even under actual complex scenes for a vision system having a frame rate of up to 2000 fps.

8437-14, Session 3

Image noise reduction in Bayer RAW domain optimized for real-time implementation and subjective quality

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Image de-noising has being a well studied problem in digital image processing. However there are a number of problems, preventing state-of-the-art algorithms finding their way to practical implementations. In our research we study these problems and provide a practical solution via a FPGA implementation of a novel noise reduction algorithm.

We identify that robustness of algorithms and their ability to handle different types of noise within a wide range of signal-to-noise ratios, need for achieving natural looking processed images and real-time performance as key problems that require solutions.

We propose a robust, real-time, multi-scale, de-noising algorithm in the Bayer raw image data space. We use an improved version of the Non-Local Mean (NLM) block matching algorithm on different levels of a Laplacian Pyramidal decomposition of an image to remove both high and low-frequency noise while preserving the image details (edges, textures, etc.) keeping algorithm complexity low. The novel improvements introduced to the standard NLM algorithm includes, setting thresholds for each block accumulation dynamically, modelling the sensor in the Bayer raw data domain to estimate the noise-levels and calculate the weights for block averaging and a novel method for non-linear data analysis to estimate the energy of details, leading to the prediction of correlation values. This guarantees detail preservation while at the same time has increased strength of filtering on image parts where no details can be found.

The first step of the proposed algorithm is to calculate the intensity of each pixel, including information on colour cross channel correlation. We note that for colour sensors with a Bayer pattern the intensity calculation is important due to two reasons: Equal decision regarding filtering or processing should be made to the three colour plains if the associated pixels belong to the same object detail. Calculating intensity also helps to obtain the image with lower noise by eliminating colour cross-channel noise, thus helping to detect image details more reliably, due to the fact that image data in colour channels in a neighbourhood of pixels is correlated, while the noise is not. Intensity calculation also eliminate chequer patterns appearing in the resulting RGB image. The second step in the proposed algorithm is to calculate noise characteristics. This calculation is performed for each pixel. In parallel with intensity and noise profile calculations, the image is passed through a set of filters: High pass filter, band pass filter, and a low pass filter. When the filtering is completed, image data, intensity and noise profile are used by the NLM filters. The resulting images from the NLM are finally sent to a final fusion block, where the colour plains are combined to create the final processed image.

We compare our algorithm against Adobe, Noise Ninja and BM3D to evaluate its performance improvements in PSNR, noise structure (spectral characteristics) and the natural look of the image. The proposed algorithm was able to achieve processing speed of 150 Mps, which is sufficient to process HD video. The algorithm was implemented on commercial grade Altera Cyclone III FPGA.

8437-15, Session 3

Real-time lossy compression of hyperspectral images using iterative error analysis on GPUs

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Hyperspectral image compression is an important task in remotely sensed Earth Observation as the dimensionality of this kind of image data is ever increasing. This requires on-board compression in order to optimize the donwlink connection when sending the data to Earth. A successful algorithm to perform lossy compression of remotely sensed hyperspectral data is the iterative error analysis (IEA) algorithm, which applies an iterative process which allows controlling the amount of information loss and compression ratio depending on the number of iterations. This algorithm can be computationally expensive for hyperspectral images with high dimensionality. In this paper, we develop a new parallel implementation of the IEA algorithm for hyperspectral image compression on graphics processing units (GPUs). The proposed implementation is tested on several different GPUs from NVidia, and is shown to exhibit real-time performance in the analysis of an Airborne Visible Infra-Red Imaging Spectrometer (AVIRIS) data sets collected over different locations. The proposed algorithm and its parallel GPU implementation represent a significant advance towards real-time onboard (lossy) compression of hyperspectral data where the quality of the compression can be also adjusted in real-time.

8438-01, Session 1

Up- and down-conversion materials for photovoltaic devices

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Up-conversion (UC) and down-conversion (DC) of sunlight are two possible routes for improving energy harvesting over the whole solar spectrum and overcoming the Shockley-Queisser limit for a single-junction photovoltaic (PV) device. The effect of adding an DC and UC layers to the front and rear of a device, respectively, is to change the incident solar spectrum. One of the materials more extensively studied for these propose have been the lanthanides or rare-earth systems, due to the suitability of their discrete energy levels for photon conversion inside a wide variety of host materials. While high quantum yields of 200% have been demonstrated with DC materials, there remain several barriers to realising such a layer that is applicable to a solar cell. These are, firstly, weak absorption of the lanthanide ions and, secondly, the competing loss mechanism of non-radiative recombination. For UC, these two barriers still exist, however an additional challenge is the non-linear nature of the UC process, thus favouring high incident powers. In this paper we review the materials used for UC and DC in PV, paying special attention to optical characterisation (absorption, fluorescence quantum yield). Subsequently, we will discuss how some of the methodologies form nanooptics cn be applied to overcome the low absorbance of the lanthanide ions, and, finally, progress towards an integrated UC/DC-PV device.

8438-02, Session 1

Fluorescent borate glass superstrates for high efficiency CdTe solar cells

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For photovoltaic applications, the cover glass is one of the key components of solar modules. For high efficiency modules, it would be advantageous to use the glass not only as a cover but also for spectral conversion. Samarium-doped borate glasses, for instance, convert the incident violet and blue part of the solar spectrum to visible red light which is more efficiently absorbed by the solar cell. Borate glasses are, in principle, suitable as solar glasses since they are highly transparent, robust and inexpensive. The chemical composition consists of boron oxide as a network former and metal oxides as network modifiers. For a ratio of two mole boron oxide and one mole metal oxide the glass network consists of the highest possible amount of four-coordinated boron, enabling the best mechanical stability. The glasses are additionally doped with trivalent samarium ions to allow for spectral conversion.

The number of solar photons being absorbed by a Sm3+-doped cover glass depends on the thickness of the glass and on the Sm3+ doping level. The absorbed photons are partially converted to photons in the red spectral range where the external quantum efficiency (EQE) of a CdTe solar cell is much better than in the violet and blue spectral range. The EQE in the latter case is mainly given by the thickness of the CdS window layer having its absorption edge at 510 nm. The internal quantum efficiency of the spectral conversion by Sm3+ was estimated in preliminary work to be approximately 50% whereby 80% of the emitted photons reach the CdTe absorber (the escape cone losses are approximately 20%). The best case scenario yields a relative increase in efficiency in the range of a few percent.

8438-03, Session 1

Strategies to tailor the UV absorption band of Eu3+:La2O3 down-shifting nanocrystals

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One of the limited parameters in solar cells is their poor absorption since they cannot absorb the broadband light arriving from the sun to the surface of our planet. Most of the photovoltaic modules comprise encapsulated crystalline silicon solar cells. These modules even show a more limited response to wavelengths below 400 nm due to the absorption of the vinyl acetate encapsulation. From another side, polymer-based solar cells suffer from the bandgap absorption of these materials, typically below 2 eV. Therefore, materials especially with nanosizes and absorbing in complementary regions of the electromagnetic spectrum and emitting in the absorption range of semiconducting polymers, can be blended with these materials to enlarge the absorption range of polymer-based solar cells and enhance their efficiency.

A very good candidate to absorb the solar energy in the UV region is Eu3+:La2O3 since it presents a charge transfer state (CTS) band between oxygen and europium ions with the most red shifted position when compared with the rest of rare earth sesquioxides. However, this CTS band is peaking below 300 nm, far below the limit of the solar spectrum arriving to the surface of the Earth.

We explored several strategies to shift the position of this CTS band towards blue wavelengths based on the use of different preparation routes and different co-doping ions. The most promising results have been obtained with Bi3+:Eu3+:La2O3 nanocrystals, that absorb in a broad band from 250 nm to 350 nm and emit in the red. Also, the results obtained in Eu3+:La2O2S nanocrystals are very promising, allowing a further red shift of the CTS band.

New approaches embedding these nanocrystals, with their surface functionalized to prevent agglomeration and disperse them better in P3HT/PCBM solar cells, have been done with good prospects.

8438-04, Session 1

Organic wavelength selective mirrors for luminescent solar concentrators

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The luminescent solar concentrator (LSC) is a simple device employing a plastic plate containing fluorescent dyes that absorb sunlight and re-emit this light, where it becomes trapped in the plate and concentrated at the edges, where photovoltaics may be used to generate electrical current. The LSC could allow inexpensive, easily adapted building integrated electricity generation. The efficiency of LSCs is limited in that a large fraction (often ~50% of absorbed photons) of the dye-emitted light is not trapped in the waveguide, becoming 'surface losses' through escaping the top and bottom of the LSC. [1]

Wavelength selective mirrors have been proposed for reducing these surface losses, which in turn lead to an increase in efficiency of LSCs. Such mirrors can be made from organic chiral nematic (cholesteric) liquid crystalline materials. Mirrors from common cholesterics have a reflection band of only 75 nm in width, much narrower than the dye

emission spectrum. Previously, we demonstrated the application of such cholesterics increased the efficiency of an LSC containing Lumogen Red 305 dye by up to 15%. [2] In this work, we show broadband reflectors made from layered chiral nematic films demonstrating an increase in LSC efficiency of over 40% in theory and up to 25% in practice, dependant on the number of re-absorptions of emitted photons by the dye molecules.

All previous research involving LSCs containing Lumogen Red 305 have assumed direct incident sunlight normal to the LSC surface. In this paper we present calculations and measurements on the effect of organic reflectors on LSCs which contain other fluorophores with different absorption/emission spectra and different spectral overlaps. Additionally, the effect of non-direct sunlight on the performance of these wavelength-selective mirrors is determined, since reflection of these mirrors is strongly dependant on the angle of the incident light.

[1] M. G. Debije, P. P. C. Verbunt, B. C. Rowan, B. S. Richards and T. Hoeks, Appl. Optics, 2008, 47, 6763.

[2] M. G. Debije, M.-P. Van, P. P. C. Verbunt, M. J. Kastelijn, R. H. L. van der Blom, D. J. Broer and C. W. M. Bastiaansen, Appl. Optics, 2010, 49, 745.

8438-05, Session 1

Concepts to enhance the efficiency of upconversion for solar applications

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Solar cells generally do not utilize sub-band-gap photons. Upconversion of these otherwise lost photons is a promising approach for more efficient solar cells. Upconversion enhances the radiative efficiency limit of silicon solar cells from close to 30% up to more than 40%. We investigate upconverters based on lanthanides. They are known for high upconversion efficiency under laser excitation. However, the achieved upconversion efficiency is still not high enough and the absorption range of these materials is too narrow for an application in photovoltaics.

We present an overview of different possibilities to enhance the efficiency of upconversion for silicon solar cell applications and show theoretical and first experimental results. The concepts can be divided into two groups. The first group comprises internal concepts, e.g., the host material itself, size effects, dopant concentration, and co-doping. The second group consists of external methods which change the physical environment around the upconverter or the excitation spectrum. This can be achieved by plasmon resonances in metal nanoparticles or by spectral concentration with infrared dyes like quantum dots, for example. Due to spectral concentration a larger fraction of the solar spectrum can be utilized by the upconverter, making it one of the most promising concepts for upconversion solar cells.

For the internal methods we will show analyses of the intensity dependent upconversion efficiency of microcrystalline upconverters with different doping concentrations and host materials. Based on a detailed rate equation model of the upconverter b-NaY1-xErxF4 the effect of plasmon resonances on the upconversion performance is estimated. To verify the predictions of this model first experiments with spherical gold nanoparticles and the microcrystalline upconverter b-NaY0.8Er0.2F4 are performed.

8438-06, Session 2

Solar light trapping and harvesting with 3D photonic crystals

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We describe designs of 3D photonic crystal silicon-based solar cells that enhance the overall absorption of sunlight using a three-section architecture consisting of less than 1 micron (equivalent bulk thickness) of silicon and no metallic mirrors. The three sections are (i) an anti-reflection (AR) layer consisting of a lattice of nano-cones placed on top of simple cubic photonic crystal (ii) the 3D simple cubic photonic crystal (average rod diameter 170 nm and 350 nm lattice spacing) that traps light through a novel parallel-to-interface refraction (PIR) effect and (iii) a chirped photonic crystal back-reflector (BR) designed to absorb near-infrared light. Each rod contains a radial P-N junction and comprises an entire solar cell, with regions between the rods filled with silica (to mechanically protect the array) up to the tip of the nano-cones. These structures exhibit exceptionally good light absorption over a broad range of incident angles from 0 to 80 degrees. They can absorb roughly 75%-80% of all available sunlight above the electronic band gap of silicon. These nano-structured photonic crystals offer additional opportunities in combined photonic and electronic management to achieve and possibly surpass the Shockley-Queisser power efficiency limit of roughly 33%.

8438-07, Session 2

Opto-electronic reciprocity and its implications for solar cells

U. Rau, Forschungszentrum Jülich GmbH (Germany)

No abstract available

8438-08, Session 2

Efficient light trapping in thin-film Si solar cells using Mie resonators

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We demonstrate an entirely new way to realize perfect impedance matching of light into a solar cell, using strongly substrate-coupled surface Mie scatterers. Arrays of dielectric nanoparticles interact very efficiently with the solar radiation and preferentially reradiate the incident light into the substrate, thus providing almost perfect anti-reflection properties. Besides the excellent anti-reflection properties, the array of Mie scatterers provides a novel light-trapping scheme for ultrathin devices, thus allowing efficient spectral conversion of sunlight.

Our work is comprised of theoretical modelling using Mie theory and finite-difference time domain (FDTD) simulations, fabrication of Mie resonators on Si(100) wafers and thin-film Si devices, and optical measurements and photocurrent spectroscopy. First, we investigate the scattering of light from dense arrays of silicon nanocylinders of different shapes and sizes (diameter 50 - 300 nm) on a Si substrate. Light is resonantly confined in the particle with an absorption cross section equal to nearly 10 times the geometrical area. Using FDTD simulations we design an optimized array with a pitch of 250 nm, particle diameter 250 nm diameter and height 150 nm. When coated with a 50-nm-thick Si3N4 layer FDTD shows this structure has an average reflectivity as low as 1.3% over the entire 400 - 1100 nm spectral range.

Next, we used optical interference lithography, nano-imprint soft lithography and reactive ion etching to fabricate the optimized array of Si nano-cylinders on top of a full 4-inch Si wafer. Total reflectivity measurements in integrating spheres show a total reflectivity of 1.3% (averaged over the AM1.5 solar spectrum) in the 450 - 900 nm spectral range, confirming the FDTD simulations. The low reflectivity is well below that of any other standard anti-reflection coating used for Si solar cells. Angle-resolved reflectivity measurements show a reflectivity below 2% for all angles of incidence ranging from -60 to 60 degrees.

Finally, we demonstrate that surface Mie scatterers enhance light absorption in ultra-thin Si solar cells. Numerical calculations show a 10% enhancement in light absorption in a 200-nm-thick c-Si layer patterned with Si nano-cylinders. The new light-coupling mechanism described in this work is applicable to any high-index semiconductor and opens new perspectives for designing high-efficiency (ultra-)thin solar cells.

Refs:

1. Plasmonics for improved photovoltaic devices, H.A. Atwater and A. Polman, Nature Mater. 9, 205 (2010)

2. Broadband omnidirectional antireflection coating based on subwavelength surface Mie resonators, P. Spinelli, M. A. Verschuuren, and A. Polman, Nature Comm. 3, in press (2012)

8438-09, Session 2

Angularly selective filters for solar cells

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To achieve higher efficiencies in solar cells one possibility is to integrate angularly selective filters, with the aim of decreasing radiative recombination and escape of non-absorbed photons. Thermodynamically, angular selectivity is equivalent to concentration. In both cases the Shockley-Queisser-Limit of non-concentrating solar cells is overcome as the consequence of a change in the ratio of the angles of incidence and emission. In concentrating systems the angle range of incidence is increased, whereas in systems with an angular confinement the acceptance angle of emission is decreased.

The same efficiencies are achieved by a combination of both, concentration and angular confinement.

Starting from a given concentrating system, angularly selective filters such as thin film stacks and two or three dimensional photonic crystals are investigated and optimized for the use in the given system.

We present results of wave optical simulations of these systems and show some of their characteristics.

The goal is not only to optimize optical filters but also to consider the whole system.

One approach is to use the optical simulation results as input values for detailed balance simulations of the solar cell. So, the main advantage is that the optical characteristics are not optimized separately, but rather the whole system is taken into account, which allows for more accurate predictions of the theoretical efficiency enhancement.

As an outlook, we show the concept of a photonic solar cell, in which angularly selective element and solar cell are combined into one optoelectronic device. In this case it should be possible to inhibit the process of radiative recombination by matching the photonic and the electric band gap. Here we present some first considerations to the design parameters of such a system.

8438-10, Session 2

Tuning the color of highly efficient, semitransparent organic photovoltaic devices

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Window integrated photovoltaics for automotive and building applications are a promising market segment for organic solar modules. Besides semi-transparency, window integrated applications require a reasonable transparency color perception. These boundary conditions are well matched by a blend of PSBTBT:[70]PCBM with an extended absorption to the infrared. We therefore fabricated and investigated highly efficient ($\eta \approx 3\%$), semi-transparent PSBTBT:[70]PCBM solar cells under different illumination scenarios such as bright sunlight or cloudy skies. However, a reasonable transparency perception does not necessarily imply good color rendering. The color rendering of items under illumination of transmitted light is of utmost importance when integrating semi-transparent photovoltaic devices in windows or overhead glazing. For example, (transmitted) white light that mainly contains blue and yellow parts of the visible spectrum will render white surfaces acceptably but is incapable of rendering reddish objects. The transmitted light through PSBTBT:[70]PCBM solar cells exhibits remarkable color rendering properties making this polymer/fullerene blend and the respective solar cells suitable for real-life window applications.

Unfortunately, most solar cells with efficient polymer/fullerene blends such as the reddish PCDTBT:[70]PCBM, neither appear color neutral nor exhibit good color rendering properties. In this work we successfully tuned the transparency color perception and color rendering properties by incorporating complementary absorbing dyes into the device. In light of roll-to-roll mass production processes for solution deposited solar cells we investigated two concepts: integration of dye doped PMMA layers into the device architecture and blending of the dyes into a highly conductive PEDOT:PSS anode. As a result, the transparency color perception of the modified devices equaled daylight and the color rendering index (CRI) approached unity while we observed only very little effect on the overall device power conversion efficiency. Another way of affecting the solar cell's color is the systematic fine tuning of thin film interferences within the device. We deliberately simulated the influence of the cathode TCO and other layer thicknesses on the light interference pattern and hence the light absorption and reflection utilizing optical parameters that were obtained in-house. By carefully selecting the electrode thickness, outstanding color perception and rendering properties can be realized for a variety of absorber materials.

These techniques allow for choosing the absorber blend independently of its natural color perception so that the entire range of highly efficient organic absorber materials is available for the fabrication of color neutral semi-transparent photovoltaic devices.

[Ref.: A. Colsmann et al., Adv. Energy Mater, 1 (2011) 599]

8438-33, Poster Session

Propagation of white light through optical fibres for CPV systems

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Optical fibres as sunlight harvesting waveguides for use in concentrating photovoltaic (CPV) systems are proposed. The selection of crystalline silicon as the end receiver sets the upper limit for concentration. Based on present day silicon cells the integrated CPV system will benefit from concentrations up to 500 suns. Despite the upper limit set by the receiver, higher concentrations are attempted initially to reach the highest possible sun concentration based on commercially available materials. Losses due to the imaginary part of refractive index are considered in order to achieve the requisite concentration ratio. Results of ray tracing modelling and simulations in feasible optical fibre configurations are presented in this paper. The configurations incorporate aspheric lenses, a simpler precursor of the Fresnel lens. Step index fibres with SiO2 as core material and preferably high numerical apertures and high incidence angles are utilised initially. Scenarios with sources of monochromatic and 1000 W/m^2 black body radiation are considered on simulations. The dependency of the transmitted angle in the fibre on the wavelength is investigated by theoretical computation based on Snell equations. For 40o angle of incidence, the transmitted angle deviates up to 22% in proportion to the wavelength for the range 0.2µm to 3.0µm. The wavelength dependent critical angle is also displayed on ray tracing as the number of internal reflections through the fibre. Simulation results display focused power up to 170000 W/m^2 at the end tip of a 1mm thick fibre from a black body source emitting 10^7 rays. Although high concentrations can be achieved in practice, for CPV applications uniformity at the end receiver is also considered as a key factor to realise acceptable cell performance.

8438-37, Poster Session

Meso-porous films of conductive polymer

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In recent years the nano- and micro processing technique progresses more and more. Here, we investigated the self-organization of polymer materials on the nano/microscale. By using the so-called 'breath figure technique' mesoporous films having the regular cavity structure on the micrometer scale can be made. The manufacture principle involves casting a polymer solution under high humidity. We used poly(styrene-co-maleic anhydride) (100mg/20 ml) and an amphiphilic poly-ion complex (polystyrene sulfonate / bishexadecyl dimethyl ammonium) (10mg/20ml) in chloroform which was cast to a glass substrate under high humidity. Those mesoporous films were immersed in an aqueous solution containing aniline, dodecyl benzene sulphonic acid, hydrochloric acid, and persulphuric acid ammonium. This is a standard mixture to produce stable colloidal polyaniline. This produces the desired polyaniline, which was confirmed by spectroscopy (green color of the film) and electric conductivity measurements. The cross sections of the film increased by increasing the number of adsorption cycles of the polyaniline. The conductivity rose, too, with the number of layers (1 layer: 10^6 [Ω] 2 layers: 10^5 [Ω] 3 layers: 10^4 [Ω] 4 layers: 10^3 [Ω], and 5 layers: 10^3[Ω]). We think that the conductive sudden change not only due to the thickness of the film but also due to the doping effect of the acid.

8438-38, Poster Session

Improved efficiencies of organic solar cells by integration of light-trapping gratings

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Harvesting of sunlight by organic solar cells is a promising method to generate clean and renewable energy in a cost efficient manner. However, the still relatively low efficiencies of organic solar cells compared to their inorganic counterparts remain as an obstacle for their commercialization.

A great challenge in this respect is to fully optimize the cell geometry in order to both efficiently collect the photo-generated excitons which are separated at the donor/acceptor interface and at the same time provide efficient transport of the generated carriers to the electrodes. One method for achieving this is by intimate mixing of the donor and acceptor material to reach small phase segregated domains and at the same time use sufficiently low cell thicknesses to provide efficient transport of carriers. However, in a planar device configuration this leads to a reduction in absorption which limits the efficiency of the cell.

To address this issue, our objective is to fabricate thin film-based solar cells with diffraction gratings that increase the light path length in the cell and thus enhance absorption in wavelength intervals matching the absorption peak of the organic active layer.

Here we present the results of inverted bulk-heterojunction organic solar cells containing gratings on the bottom-electrode, which trap the incident light into the active layer and enhance the device efficiency. In this work, two different devices containing two different molecular blends (P3HT:PCBM and PCPDTBT:PCBM) as active layers were investigated and gratings were respectively tuned to couple light at the same wavelength as the absorption peak in each blend, thereby enhancing the solar cell efficiency.

8438-39, Poster Session

The effect of ligand substitution and water co-adsorption on the adsorption dynamics and energy level matching of amino-phenyl acid dyes on TiO2

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We study the effect of extension of pi-conjugation of organic dyes - a typical procedure in dye design for dye-sensitized solar cells - on the energy level matching with the oxide surface and its dependence on atomic motions. We also consider the effect of water contamination.

We perform a comparative theoretical analysis of adsorption of dyes NK1 (2E,4E-2-cyano-5-(4-dimethylaminophenyl)penta-2,4-dienoic acid) and NK7 (2E,4E-2-cyano-5-(4-diphenylaminophenyl)penta-2,4-dienoic acid) on clean and water-covered anatase (101) surfaces of TiO2.

A slab model of the oxide surface is used, and DFT calculations are used to study adsorption geometries and energy level matching by monitoring Kohn-Sham orbital energies.

At a fixed geometry, ligand substitution away from the anchoring group changes the energy level matching between dye's LUMO and oxide's conduction band due to a better stabilization of the LUMO in the larger dye.

Molecular dynamics simulations at different temperatures for dyes adsorbed in a monodentate and bidentate configurations show that atomic motions have a strong, dye-dependent, and adsorption configuration-dependent effect on injection. In theoretical studies of the dye / semiconductor interface, it is usually assumed that the dye stays attached to the surface in the most energetically favored configuration. In dyes attached via a carboxylic acid group, the bidentate binding is usually assumed. Here, we show that monodentate and bidentate binding of the NK1,7 dyes to TiO2 have similar adsorption energies even as the injection from the bidentate mode is expected to dominate. Nuclear vibrations lead to an increased driving force for injection from the monodentate configuration, with a smaller effect on the bidentate mode. The smaller driving force predicted for NK7 is in agreement with recent transient absorption measurements indicating slower injection from NK7 vs. NK1.

When the dyes are co-adsorbed with a monolayer of water, it has a strong effect on adsorption, inducing dye deprotonation and affecting strongly and differently between the dyes the energy level matching. It leads to a shut-off of the injection from the bidentate adsorption configuration of NK7. This suggests water contamination as another reason for the experimentally observed slower injection from NK7.

8438-40, Poster Session

The negative effect of gold nanoparticles on the efficiency of P3HT:PCBM solar cell

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Gold nanoparticles has shown to have a positive effect on the efficiency of P3HT:PCBM solar cells [1-4]. However our study shows a negative effect of AuNPs on the efficiency of the cell. 30 nm gold nanoparticles with a surface density of 215/μm2 were deposited on the APTMS modified indium tin oxide electrode. Layers of PEDOT:PSS and P3HT:PCBM was spin-coated on top of ITO respectively and samples are completed by evaporating a 100 nm of silver electrode and finally backed in 140°C. The power conversion efficiency decreased about 87%. The impedance of cells were also measured. It seems that AuNPs cause the impedance of the whole cell to decrease to a negligible value. But this huge decrease did not result in a good short circuit current. However the origin of lowering the impedance was not investigated. It can be caused directly by nanoparticles or is a e.g. annealing effect caused by nanoparticles is not investigated.

[1] K. R. Catchpole and A. Polman, "Design principles for particle plasmon enhanced solar cells," Applied Physics Letters, vol. 93, no. 19, p. 191113, 2008.

[2] M. Park, B. D. Chin, J.-W. Yu, M.-S. Chun, and S.-H. Han, "Enhanced photocurrent and efficiency of poly(3-hexylthiophene)/fullerene photovoltaic devices by the incorporation of gold nanoparticles," Journal of Industrial and Engineering Chemistry, vol. 14, no. 3, pp. 382-386, May 2008.

[3] J. H. Lee, J. H. Park, J. S. Kim, D. Y. Lee, and K. Cho, "High efficiency polymer solar cells with wet deposited plasmonic gold nanodots," Organic Electronics, vol. 10, no. 3, pp. 416-420, May 2009.

[4] A. J. Morfa, K. L. Rowlen, T. H. Reilly, M. J. Romero, and J. van de Lagemaat, "Plasmon-enhanced solar energy conversion in organic bulk heterojunction photovoltaics," Applied Physics Letters, vol. 92, no. 1, p. 013504, 2008.

8438-41, Poster Session

The influence of particle size in printed TiO2-layers on the efficiency of dye sensitized solar cells

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The mesoporous TiO2 layer is probably the most important layer in a dye sensitized solar cell mainly because the dye adsorption and the electron transport depend on it. However the photoactivity optimum for nanoparticle and pore size is respectively 7.5 and 5.5 nm[1], the particle size for the mesoporous layer has been optimized and found to be about 15-20nm [2,3]. This difference, addressed to the lower electron mobility due to the increased grain boundary, could be overcome by using a mixture of the smaller nanoparticles with 50-100nm particles[4]. In this work stable dispersions of TiO2, obtained by hydrothermal synthesis, have been deposited on glass/ITO patterned substrates by two different printing techniques and compared to layers printed with commercial TiO2 paste with different particle sizes. For the screen-printing the semi-automatic ISIMAT 1000P was used and the DIMATEX 2831 was used for inkjet-printing. To use these layers in a working device such as a Grätzel-solar cell, as well the uniform dense layer as the mesoporous layer can be printed by the above mentioned techniques. Optical Microscopy, profilometry and Scanning Electron Microscopy (SEM) are performed to study the roughness and surface structure of the printed layers to finally end up with perfect structured TiO2-layers for the use in dye sensitized solar cells (DSSC). Fill Factors, open circuit voltages, short circuit currents and finally efficiencies are compared between the spincoated and the printed DSSC to draw a conclusion on the optimal printing technique for these layers as well as on the optimal particle size for the different deposition techniques.

[1] Y. Sakatani et al. Optimised photocatalytic activity of grid-like mesoporous films: effect of crystallinity J. Mater Chem., 16, 77-82 (2006)

[2] C. J. Barbé et al., Nanocystalline Titanium Oxide Electrodes for Photovoltaic Applications, J. American Ceramic Society, 80 (12) 3157-71 (1997)

[3] M. Grätzel, J. R. Durrant, Dye-sensitized mesoscopic solar cells, Nanostuctured and Photoelectrochemical systems for solar photon conversion (2008)

[4] L. Miranda, A Chianese Chemical engineering trans. Volume 17, 975 (2009)

8438-42, Poster Session

Black silicon for solar cell applications

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We present experimental results and rigorous numerical simulations on the optical properties of Black Silicon surfaces and their implications for solar cell applications.

The Black Silicon is fabricated by reactive ion etching of crystalline silicon with SF6 and O2. This produces a surface consisting of sharp randomly distributed needle like features with a characteristic lateral spacing of about a few hundreds of nanometers and a wide range of aspect ratios depending on the process parameters.

Due to the very low reflectance over a broad spectral range and a pronounced light trapping effect at the silicon absorption edge such Black Silicon surface textures are beneficial for photon management in photovoltaic applications.

We demonstrate that those light trapping properties prevail upon functionalization of the Black Silicon with dielectric coatings, necessary to construct a photovoltaic system. Furthermore we investigate the influence of such overcoatings on the reflectance properties and present additional measures that can be taken to suppress residual reflections from those functionalized surfaces.

The experimental investigations are accompanied by rigorous numerical simulations based on three dimensional models of the Black Silicon structures. Those simulations allow insights into the light trapping mechanism and the impact of geometrical parameters like feature size, feature spacing and wafer thickness onto the optical performance of the Black Silicon.

Finally we use an analytical solar cell model to relate the optical properties of Black Silicon to the maximum photo current and solar cell efficiency in dependence of the solar cell thickness. The results are compared to standard light trapping schemes and implications especially for thin solar cells are discussed.

8438-43, Poster Session

Mc-Si nanowire fabricated by metal assisted chemical etching for solar energy conversion

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High aspect ratio silicon nanowire (SiNW) forest is a promising architecture for applying in solar energy conversion system. By using solution based metal assisted chemical etching, large area of high quality SiNWs was formed on the multi-crystalline silicon substrate (Mc-Si). Mc-SiNW forest can greatly suppress diffuse and specular reflectance, demonstrating optical absorption more than 95% in the wavelength range of 300-1000 nm. Here we studied Mc-SiNWs for photoelectrochemical hydrogen generation. When the Mc-SiNWs contacted with electrolyte, NW array architecture can provide sufficient optical absorption along its axial direction, while facilitating collection of carriers radially over a distance sufficiently short to compensate for a short minority carrier collection length. This prototype cell showed enhanced open circuit voltage, also demonstrated better stability than its bulk counterpart. By impedance test, we confirmed that NW-electrolyte junction can indeed effectively extract the photogenerated carriers. However, we found that, with increase of Mc-SiNW length, lots of surface states were introduced, leading to severe surface recombination. As a result, photocurrent was reduced. To solve this issue, the NW length should be well controlled; or adequate surface passivation on NW such as TiO2 by atomic layer deposition (ALD), is required.

8438-44, Poster Session

Optical characterization of TCO films on fluorescent borate glasses for high-efficiency solar cells

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Solar cells with a cover glass have a poor response in the blue and near UV spectral range due to absorption in the glass and the front

contact layer. The efficiency of these solar cells can be improved by replacing the top glass by a spectral converter, i.e. a frequency down-converter, without modifying the solar cell itself. Potential candidates are fluorescent, samarium-doped borate glasses. They convert the incident violet and blue part of the solar spectrum to visible red light, which is more efficiently absorbed by the solar cell. Borate glasses are suitable as solar glass since they are highly transparent, robust and inexpensive. The chemical composition consists of boron oxide as a network former and metal oxides as network modifiers.

In this work, borate glasses are used as substrates for the deposition of transparent conductive oxides (TCO). Two different TCO systems were investigated, namely indium tin oxide (ITO) and aluminium-doped zinc oxide (AZO). The deposition was done by radio frequency magnetron sputtering at room temperature. The layer thickness was subsequently analyzed by profilometry and scanning electron microscopy. Optical simulations provided the refractive indices of the TCO films. As well as optical parameters, electrical parameters such as sheet resistance and I-V characteristics were determined. Moreover, the influence of different sputter parameters, i.e. gas pressure, oxygen flow, or substrate temperature on the optical and electrical properties of the deposited films were investigated.

Finally, to evaluate the potential of fluorescent borate glasses as a substrate material for thin film photovoltaics, two small modules were manufactured by depositing an additional silicon absorber layer and an aluminium back contact on the TCO-coated borate glasses. A fluorescent, Sm^{3+}-doped and an undoped borate glass were deposited simultaneously and the properties of both cells were analyzed and compared.

8438-45, Poster Session

An LED-based solar simulator

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A solar simulator is a device which provides an approximate illumination of the solar spectrum. Solar simulators are an essential component in solar cell standardisation as they facilitate solar cell measurements, such as current-voltage readings under a known spectrum without the natural variability of outdoor conditions.

One limitation of these solar simulators is that their lamps have short lifetimes (~1000 hours) which can produce a great deal of heat. One relatively inexpensive method alternative to current solar simulators is to replace the lamp with light emitting diodes (LEDs). LEDs are preferable as they are cool, economical and highly energy efficient with extended lifetimes (~10,000 hours).

The artificial light produced from the solar simulator is controlled in three dimensions; spectral match, spatial uniformity and temporal stability and each of these dimensions is further classified into an A, B, C class. Finally, the solar spectrum is categorised by the integrated irradiance across several wavelength intervals e.g. AM0, AM 1.5D and AM 1.5G.

The artificial light from a solar simulator is typically produced from either a Xenon or Sulphur lamp. As the output differs considerably from the AM 1.5G spectrum, filters and spectral matching techniques are necessary. By strategically placing LEDs with appropriate wavelengths in difference planes and geometries and using suitable controls for optical modulation, it is anticipated that the collective spectral output from the LEDs can be matched to the AM 1.5 global spectrum.

8438-47, Poster Session

Impact of laser ablated Al2O3 passivation layers from black Si surfaces on the optical surface properties

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Inductive coupled plasma reactive ion etching (ICP-RIE) of silicon enables excellent broad band and wide angle antireflective surface properties. The stochastically emerging needle like nano-structures let the silicon surface appear optically black due to its high absorption coefficient of over 97%. Concomitant, highly enhanced surface recombination is introduced. The latter, may be effectively suppressed by a well suited passivation layer of Al_2O_3 deposited by thermal ALD. Laser ablation is commonly used in the PV industry to open local contact areas in dielectric passivating stacks. Herein, we show the feasibility to ablate alumina thin films from ICP-RIE structured black silicon (b-Si) solar cell front surfaces. Micro-structural geometric analysis by focussed ion beam and SEM reveal slight structural changes in the zone of ablation which are believed to be beneficial for contact formation. Simultaneously, neither the deposition of Al_2O_3 layers of varying thickness nor their ablation lead to a very significant degradation of the optical surface properties.

8438-48, Poster Session

Optical properties of lanthanide-organic dyes for spectral conversion encapsulated in porous silica nanoparticles

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Lanthanide based dyes belong to one of the most promising fields of photovoltaic research, combining high quantum yields and large Stokes shifts. However, many challenges are still being faced when working with organic dyes for spectral conversion: their thermal and chemical stability, which can greatly influence the working life of the dyes; the absorption band positioning, which depends on the organic part of the dye, the so called "antenna"; self-quenching mechanisms, which lead to a photoluminescence emission loss. As has been already shown, the chemical composition of the surroundings of the dyes has a fundamental role in their properties. This work focuses on studying the optical and chemical properties of europium-based dyes embedded into a silica matrix; the in-house synthesized dye consists of a bis(2-(diphenylphosphino)phenyl)ether oxide (DPEPO) ligand and three hexafluoroacetylacetonate (hfac) co-ligands coordinating a central europium ion. The dyes have been included in porous core-shell particles, to study their optical properties once embedded in a solid dielectric matrix. Silica has been used as the host material, due to the possibility of obtaining mono-disperse spherical particles through the Stöber reaction, which grants a high degree of repetitiveness and control on the reaction products. The optical properties of the resulting samples have been characterized by photoluminescence emission and excitation measurements. The results have then been compared with the data obtained with commercially available dyes (BASF Lumogen family) in similar conditions.

8438-49, Poster Session

Effects of photonic structures on upconversion

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Upconversion of sub-band gap photons presents a possibility to overcome the Shockley-Queisser efficiency limit for silicon solar cells.

Using an appropriate material, like erbium-doped NaYF4, two low-energy photons can be converted into a photon having enough energy to generate an electron-hole pair in the semiconductor. Thus, attaching an upconverting material to the rear side of a bifacial silicon solar cell can increase the device efficiency.

Upconverting materials available today show conversion efficiencies that are still too low for the application within the system described above. However, as upconversion is a non-linear process, the upconversion efficiency can be increased by enhancing the local field intensity of the incoming photons. One possibility to enhance the fields that has been studied is the exploitation of plasmon resonances in the vicinity of metallic nanoparticles. A second approach, which is followed here, is to use photonic structures for this purpose. Simulations of two-dimensional photonic crystals show that very high field enhancements can be achieved within these structures. Additionally, the photonic crystal changes the local photon density of states around the upconverter. In this way, the transition rates between the different states in the upconverting material can be influenced. The goal of this approach is to enhance the upconversion efficiency by the use of photonic structures.

In this work, a rate equation model for NaYF4 doped with Er3+ is coupled with FDTD simulations to obtain the local field enhancement. Furthermore, we take into account modified transition rates that are influenced by photonic effects. Thus, the modifications in the transition probabilities can be simulated and the photonic structures can be optimized in order to obtain large field enhancements and high probabilities for the relevant transitions while suppressing others. Hence, embedding upconverting material into photonic structures, presents an approach to enhance the upconversion efficiency.

8438-50, Poster Session

Characterization of microcrystalline I-layer for solar cells prepared in low temperature: plastic compatible process

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Microcrystalline silicon films deposited in the PECVD process constitute a very promising way to manufacture a low cost and large area thin film devices such as solar cells or thin film transistors (Schropp R.E.I., Amorphous...,1998). The PECVD method has been well developed and allows fabrication of high quality films, however, it requires high temperature processing (~400°C) (J.K. Rath, Appl.Phys.A.2009). Most common, lightweight flexible substrates (PET, PEN) are not compatible with temperatures above 200°C. Thus, development of PECVD deposition methods for temperatures below 200°C, which result in a good quality films, is desirable. Additionally, accurate electrical and physical characterization of deposited layers is crucial.

In this study we report processing and characterization results of silicon microcrystalline intrinsic layer made in plastic substrate compatible process. In addition, developed and evaluated layer was used to manufacture p-i-n solar cell for IV and quantum efficiency characterization.

Investigated microcrystalline silicon intrinsic layer was grown in the PECVD 13.56 Mhz process and temperature of 150°C. Prior silicon deposition samples were solvent cleaned and dried. Consequently, deposition process was performed at 2 Torr gas pressure, 10W plasma power, 1:100 of SiH4:H2 gases dilution and growrate 0.5 A/s. These parameters were defined based on literature review and previous experiments (A.V. Shah, Solar Energy Materials and Solar Cells, 78, 2003). Importantly, the deposition process was done on several different rigid substrates (glass, silicon, crystalline silicon) accordingly to requirements of characterization method.

After deposition samples were transferred to evaporation chamber and chromium electrodes through metal mask were evaporated. Then, the electrical properties - dark and under illumination conductivity tests were performed. To complete conductivity measurement, the layer thickness measurements were completed by using profilometer.

The structural properties and the crystal volume fraction were investigated by using Raman spectroscopy. The XRD method was used to extract the information about grain size and orientation of microcrystals. The transparency and reflectance measurements resulted in the optical bandgap of deposited layer. The AFM examination determined the roughness of deposited layer and verified the data related to grain size, obtained by XRD tests. The FTIR analysis was done on deposited sample to detect the Si-H bonds and their relative intensity. The TEM measurements visualized the deposited microcrystalline layer and determined the seed layer thickness.

Finally, based on the data from measurements the solar cells with p-i-n structure were fabricated and measured. In addition to external and internal quantum efficiency measurements, the AM1.5G IV measurements resulting in Isc, Voc, FF and Rs, were conducted.

Characterization of deposited intrinsic layer indicates worse electrical properties compared to films deposited in higher temperatures. It is mostly caused by high porosity and voids within the microcrystalline structure, which were documented by FTIR and TEM measurements. Nevertheless, AFM, XRD and Raman measurements prove that low temperature fabrication of microcrystalline intrinsic layers is a very promising option, however, needs further development to increase the overall efficiency of flexible solar cells.

8438-51, Poster Session

Laser thermoreflectance for semiconductor thin films metrology

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Successful implementation of a high-efficient laser system for thin film solar cells scribing necessitates an appropriate experimental approach to investigate and quantify the irreversible thermal effects caused by short-pulse laser irradiation. It is a crucial task for finding the optimum laser operation mode providing a high scribing reproducibility with a minimum heat affected zone in the vicinity of scribed areas.

In this paper, we address the compound semiconductor thin films off-line characterization using a thermoreflectance-based metrology. Particularly, we experimentally investigate the thermal properties of polycristalline cadmium telluride (CdTe), a commonly used solar cell absorber material. The experimental setup consisting of a nanosecond pulsed Nd-YAG heating laser, a continuous probe laser, and high-speed photodetectors implements both the rear-side and the front-side measurement configurations. The former appears to be especially suitable for the characterization of thin (less than 1µm) CdTe films. The typical thermal diffusivity value obtained in our experiments with 0.5 µm thick CdTe films is about 4x10-6 m2s-1. The later configuration, dedicated to thick (> 2 µm) films measurement, is more suitable for evaluation of the irreversible modifications CdTe thermal properties related to the laser ablation process. In our work, the front-side measurement configuration has been used to investigate 5 µm thick CdTe films ablated by nano and picosecond laser pulses.

The temperature response of the CdTe thin film to the nanosecond heating pulse has been numerically investigated using the finite-difference time-domain (FDTD) method. CdTe optical parameters found in literature and measured directly on samples by ellipsometry have been used. The computational results were compared with the experimental ones. Optimum conditions for thin film thermal properties in front-side and rear-side configurations were determined.

8438-52, Poster Session

Ligand exchange and photoluminescence quenching in organic-inorganic blends poly(3-hexylthiophene) P3HT:PbS

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Long alkyl chain ligands such as oleic acid (OLA) which cover the as-prepared PbS nanodots act as an insulating layer that impedes efficient charge transfer in PbS nanodots:polymer hybrid solar cells. The replacement of OLA with tailored ligands of an appropriate chain length is needed to achieve a noticeable enhancement of photovoltaic performance. Several studies have centered on the ligand exchange prior to casting the PbS film[1-3]. However, this post synthesis approach requires careful consideration when choosing or synthesizing the desirable ligand. Recently, a new approach that will allow direct chemical ligand replacement in a blended mixture of PbS:P3HT has been demonstrated [4-6]. In this contribution, the latter approach (post-fabrication) was compared with the post-synthesis ligand exchange. We investigated the effect of the ligand exchange processes to the charge separation dynamics in the P3HT:PbS blends by steady-state and time-resolved photoluminescence (PL). Hexanoic acid and acetic acid were used as a short-length ligand for the post fabrication approach while decylamine, octylamine and butylamine were used for the post-synthesis approach. As expected decreasing the chain length of the ligand led to increase P3HT fluorescence quenching. The results suggest that the quenching of the P3HT fluorescence is dominated by photo-induced electron transfer to PbS quantum dots (QDs) as indicated by quenching dependent on QDs surface chemistry and the absence of enhancement of PbS luminescence due to energy transfer. In addition, the fluorescence quenching also more prominent in the P3HT with lower regioregularity (RR) suggesting difference in blend phase separation due to more densely packed nature of conjugated polymer with higher RR.

References

1. Konstantatos G, Howard I, Fischer I, Hoogland S, Clifford J, Klem E, Levinna L, Sargent E H, Nature 442 180 (2006)

2. Murray C B, Norris D J, Bawendi M G J. Am. Chem. Soc. 1993, 115, 8706-8715.

3. Porter V J, Geyer S, Halpert J E, Kastner M A, Bawendi M G J. Phys. Chem. C 2008, 112, 2308-2316.

4. Seo J, Kim S J, Kim W J, Singh R, Samoc M, Cartwright A N and Prasad P N Nanotechnology 20 095202 (2009).

5. Seo J, Cho M J, Lee D, Cartwright A N, Prasad PN, Adv. Mater. 2011, 23, 3984-3988

6. Konstantatos G, Levina L, Fischer A, Sargent E H, Nano Letters 2008 Vol. 8, No. 5 1446-1450

8438-53, Poster Session

Correlation between surface topography and short circuit current density for thin film silicon solar cells

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The scattering of light by the textured transparent conductive oxide (TCO) in thin-film silicon solar cells is frequently described by transmission haze and angular resolved scattering (ARS) measured at the interface between the TCO and air. The scattering is expected to improve the light trapping but a clear relation between short circuit current densities and scattering properties of the TCOs has not been found. An important disadvantage of the measurement configuration is that in real thin-film silicon solar cells the TCO/Si interface is relevant.

We use the phase model developed by Dominé et al. [1] to calculate the scattering properties at the transition into air and into silicon. The model takes into account the measured surface topography and the optical constants of the adjacent media. For a series of cells on ZnO:Al with different surface topographies, ARS and the transmission haze into a µc-Si:H half space are calculated. From these results, a quantity containing the total transmission of the TCO, the expected scattering angle and the transmission haze into silicon is derived and compared to the short circuit current densities of µc-Si:H solar cells. A good agreement is found demonstrating the validity of the simulation. .

It will be shown that for artificially modified textures an increase in the short circuit current density and thus the efficiency of thin-film silicon solar cells can be achieved.

[1] D. Dominé, F.-J. Haug, C. Battaglia, and C. Ballif, J. Appl. Phys. 107, 044504 (2010)

8438-55, Poster Session

Structural and electrophysical properties of femtosecond laser exposed hydrogenated amorphous silicon films

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Five amorphous hydrogenated silicon (a-Si:H) films were obtained with plasma enhanced chemical vapor deposition. The produced a-Si:H films were exposed by femtosecond pulsed Ti:sapphire laser with the wavelength of 1030 nm and the pulse duration < 280 fs. Sample 1 is a non-exposed a-Si:H film, from sample 2 to sample 5 the laser intensity rose from 10^11 to 10^12 W/cm^2 continuously. The information about the films structure was obtained with the Raman spectra analysis at excitation radiation wavelength 488 nm. The spectral dependence of the absorption coefficient (αCPM) was measured with the constant photocurrent method. In order to perform the electrical and photoelectrical measurements aluminum contacts were deposited on the film surface. The conductivity, photoconductivity and absorption coefficient dependences measurements were performed at the room temperature and one atmosphere.

In the present work it has been found that the irradiation of the a-Si:H films with the femtosecond laser causes the formation of the region with the microcrystalline structure in the original material. It has been defined that the laser beam scanning geometry and the irradiation intensity specify the structure of the obtained films, which on its turn specifies their optical and electrical properties.

8438-56, Poster Session

Conductive and protective diamond like carbon coatings on Si and glass substrates

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Modified plasma enhanced chemical vapor deposition technological device worked out for preparing transparent conductive and protective diamond like carbon (DLC) coatings on the surface of monocrystalline Si and glass substrates. Optimal technological parameters for obtaining the mentioned films have been derived experimentally. Bias voltage frequency have been changed in the region of 150-450kHz. Optical and mechanical properties of DLC films have been investigated and feedback with the technological parameters have been provided in this way. Thicknesses of protective coatings have been deposited in the 70nm-200nm range. Refractive indices of DLC films have been obtained in the 1.57-2.4 range. Depending on technological parameters transparencies of DLC films in the visible region of spectra have been recorded in the range 83-89%. Specific resistivity of DLC films have been obtained in the region 1.5*10-4- 9.5*10-4 Ohm*cm. Wear resistance tests have been carried out and it has been proved that deposited films have enough mechanical hardness for protecting the substrate from external climatic influences. It cleared out that the surfaces of prepared films are hydrophobic. Obtained films have been proven to be cost effective protective and conductive coatings for PV cells applications.

8438-58, Poster Session

Improved photovoltaic performance of Si nanowire solar cells integrated with ZnSe quantum dots

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Subwavelength Si nanowire (SiNW) arrays have been increasing interest for use as an antireflection layer in photovoltaic devices owing to their unique optical properties such as superior antireflection characteristics and omnidirectional light absorption over a broad wavelength range at various angles of incidence. Despite its obvious advantages of light harvesting, however, conversion efficiencies reported to date in SiNW solar cells are generally lower than those of conventional crystalline Si solar cells due to remarkable reduction of quantum efficiency especially in a short wavelength region. A large surface area with a heavily doped thick emitter in SiNW arrays causes the increase in surface and bulk recombination losses. Consequently, improved light absorption while avoiding serious degradation in electrical parameters is of critical importance for obtaining a high efficiency in SiNW solar cells.

In this paper, we suggest an effective way using ZnSe quantum dots (QDs) to improve the conversion efficiency in antireflective SiNW solar cells. A SiNW/ZnSe QDs hybrid solar cell presents considerable enhancement in external quantum efficiency (EQE) over broadband range owing to two major benefits, i.e., light trapping and photon down-conversion. Superior antireflection characteristics of ZnSe QDs resulted in additional increase in light absorptance while decreasing the wire length required for obtaining the efficient light absorption. A highest short circuit current (Jsc) of 29.18 mA/cm2 was achieved under a short wire length of 250 nm by integrating the ZnSe QDs. The EQE enhancement of ~30% in a certain wavelength (=400 nm) revealed a frequency down-conversion by ZnSe QDs contributed to efficiency enhancement.

8438-59, Poster Session

Solar cell degradation: an experimental study

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Shunt defects are primarily responsible for deterioration of solar cell performance. These defects can be either process induced or material induced. These defects can develop with time and limit the life time performance of the device. The present study compares the degradation characteristic of three kinds of solar cell i.e. monocrystalline, polycrystalline, and organic. Both CCD imaging and Lock-in thermography techniques have been used. A Peltier cooled 12-bit CCD camera (PCO sensi-cam) is used for visible wavelength imaging. Thermo-Sensorik camera (InSb-640 SM) has been used for near infra red imaging. Both Dark Lock-in thermography (DLIT) and Illuminated Lock-in thermography (ILIT) has been implemented. Shunts, which cause losses in efficiency of solar cell, are detected by applying suitable bias in DLIT. Either a reverse bias is applied to increase current in shunt position or forward bias applied to detect weak shunts in DLIT mode. Improved spatial resolution of the thermographic images is obtained in ILIT mode, which works under realistic operational conditions of solar cell. ILIT is performed under illumination of pulsed light with the solar cell in open-circuit conditions. Lock-in frequency and intensity of excitation source affects the spatial resolution and defects can be selectively imaged by changing the intensity of excitation source. The lock-in technique is found to be suitable for detection of temperature modulation less then 0.1mK and hence can be effectively used for detection of all kind of shunts. The investigation of different kind of solar cell demonstrates the effect of material properties on shunt defect.

8438-60, Poster Session

Nanoplasmonics for photovoltaic applications

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Plasmonics has become a focus of recent research in photovoltaic application primarily due to their effect in enhancing the absorption efficiency of semiconductor solar cell. In this paper a review of different approaches that have been proposed to integrate plasmonics technologies in solar cells is presented. It has been observed that a range of metallic nanostructures that show plasmon resonance wavelength in visible and near-infrared regime can be utilized to increase the coupling of light into the solar cell. This is widely used to increase the efficiency of light that can be trapped in thin layer of active region as in thin film technologies. In this review paper, more attention is given on the techniques of fabricating the metallic nanoparticles and the ways to control their plasmon resonance wavelengths. The role of the shape, size, dielectric permittivity of the environment and the type of the metallic nanoparticles for tuning the resonance wavelength are analyzed. Furthermore, the cluster of nanoparticles gives different resonance wavelength from the individual nanoparticles due to the far field, near field and dipolar coupling among the nanoparticles. In conclusion, we show how the plasmon resonance can be engineered to increase the absorption efficiency of conventional solar cell.

8438-61, Poster Session

Simulation of optical properties of percolation type electrode for thin film solar cells with silver nanowires

S. Yan, J. Krantz, C. Pflaum, C. J. Brabec, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany)

Silver nanowire films are a newly introduced choice for transparent electrodes in thin film solar cells. Simulation is an adequate and economic method to analyse and predict the optical properties of these films. We simulate the optical behavior of such films by solving Maxwell equations. The simulation technique is a finite integration technique (FIT) combined with a time harmonic inverse iteration method (THIIM) to handle the negative permittivity of silver. Parallel computation on high performance computers(HPC) is used to meet the large computational requirement of the problem. In agreement to preliminary experimental results, the simulation results show that transmission of light is larger than expected by a simple ray-tracing model. This shows that both effective index considerations and plasmonic effects play an important role for the light transmission properties of a silver nanowire film.

8438-62, Poster Session

Emission of Rhodamine B in PMMA opals for luminescent solar concentrators

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Luminescent solar concentrators (LSC) are able to concentrate diffuse and direct sunlight without the need for tracking. Conventional LSCs consist of transparent plates that are doped with luminescent materials. Light incident on the concentrator is absorbed by the luminophores and emitted in the plate in an isotropic way. Most of this light is trapped inside by total internal reflection, where it is guided to solar cells at the edges. Light directed to the surfaces, however, is lost in the escape cone. A second loss mechanism is reabsorption of emitted light on its way to the edges. This phenomenon occurs when light is emitted in the absorption range of the luminophore.

To overcome these losses we embed the luminescent material in photonic structures. Photonic structures can be used to influence the emission characteristics such that emitted light is redistributed spatially and spectrally. Thus, emission in certain directions can be suppressed; an effect that we use to enhance the light guiding efficiency of LSCs. Further, inhibited emission in the absorption range of the luminophore can reduce reabsorption losses.

For this purpose, we fabricated polymer opals as they provide a cost-effective approach to 3D photonic crystals. The organic dye Rhodamine B was embedded in the PMMA beads during the polymerization process. The opals were designed to have a photonic band gap in the emission range of the dye.

The fabricated samples were optically characterized to investigate the influence of the photonic structure on the emission of the dye: the photoluminescence was measured angle-resolved to analyze directional enhancement and suppression. Furthermore, light collection efficiency measurements of the concentrator were performed. It turns out that high structural quality has to be achieved in the opal fabrication. Especially cracks in the opal films are crucial to the light guiding capability.

8438-63, Poster Session

Optical properties of AlTiO selective transmitting layers for transparent solar cell applications

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Transparent solar cells have drawn much attention for building-integrated photovoltaic (BIPV) application. While dye-sensitized solar cells (DSSCs) are the most important technology in the BIPV field, semitransparent thin film Si solar cells are emerging as an alternative to the DSSCs. The thin film Si solar cells based on the well-established fabrication process are superior in scalability as well as in energy efficiency compared with the DSSCs. The highly reflective layer is often introduced between a Si absorber layer and a back electrode to reflect transmitted light back to the absorber layer. The selective transmitting layer, transmitting visible light and reflecting infrared light, can substitute for the highly reflective layer in order to achieve the high-efficient semitransparent solar cells. Recently, the selective transmitting property of the AlTiO (ATO) thin film grown by atomic layer deposition (ALD) was reported. Since the ALD technique has the demerit of a slow deposition rate, a highly productive deposition method for the ATO film growth should be developed for commercialization. Thus, we prepared ATO selective transmitting layers using sputter-deposition and investigated their optical properties. The ATO layers were formed by reactive co-sputtering from the Al and Ti targets in oxygen atmosphere. The compositions and thicknesses of the ATO layers were controlled by varying deposition parameters, and corresponding changes in transmittance and reflectance were measured. The transmittance was mainly influenced by the atomic ratio of Al to Ti, whereas both the composition and the thickness of the ATO layers affected the reflectance. The reflectance decreased and then increased with increasing wavelength, and its minimum depending on the composition and the thickness of the ATO layers was found around the wavelength of 700nm. This raised reflectance in the infrared regime supports the possible use of the sputter-deposited ATO layers as a selective transmitting layer in semitransparent thin film Si solar cells.

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8438-64, Poster Session

Absorption enhancement due to grating structures for ultrathin silicon solar cells

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Light trapping due to rough interfaces is a common and industrially applied technique in amorphous silicon thin film solar cells. The induced scattering enhances the absorption and consequently the conversion efficiency of the device. However, decreasing the absorber layer thickness which results in a reduction of light induced degradation (Staebler-Wronski effect), the absorption enhancement due to scattering becomes less efficient. Especially for ultra thin solar cells with an absorber layer thickness of about 150 nm, alternative light scattering structures are required.

Our aim is to evaluate the absorption enhancement in ultra thin solar cells due to grating structures integrated in the device. We support our experimental work by detailed optical modelling to understand the internal light propagation.

The one- and two-dimensional grating structures, consisting of a transparent conductive oxide (TCO) on a glass substrate, are produced by holographic lithography method. The TCO material and the grating structures are characterized by ellipsometry, atomic force microscopy and optical spectrophotometry in order to determine the reflection, transmission and the angular distribution function of the diffracted light. To evaluate light trapping effects in the device, ultra thin amorphous silicon solar cells are deposited by PECVD method on substrates with different gratings and subsequently characterized. The results are used to calibrate our finite-difference time-domain (FDTD) method simulations. The modelling approach aims to deliver a prediction and evaluation of the effect of more complex structures, like hexagonal lattices or anisotropic gratings, which are also producible by holographic lithography.

8438-65, Poster Session

Novel method of forming micro random pattern from polystyrene gel deposition

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Surface structures are important for optical confinement in solar cells, for super hydrophobic surfaces, etc.. One can use the well-developed semiconductor manufacturing technology to form those structures. However, to produce large-areas in large numbers the semiconductor manufacturing technology is too costly to implement. Here we provide a novel method of forming micro random pattern from polystyrene (PS) ethyl acetate solution with added acetate acid in controlled humidity of 40-70% relative humidity. The micropattern is formed by spin coating polystyrene solution. Optical microscopy revealed that a pattern with micrometer-sized droplets having a narrow size distribution is formed. The spacing between neighboring microdroplets is several times their diameter with a random angular distribution. The size and pattern distribution can be controlled by the evaporation time of the solvent. Our experiments showed that the coating method is not limited to spin coating, but also spray coating, blade coating, and brushing coating can be used. Moreover these methods are indifferent of surface condition. So, the surface of 100 micron diameter glass beads, aluminum foil for food, hydrophilic and hydrophobic glass can be coated. Because their pattern is due to polystyrene gel particle deposition from solution, there is a very low effect surface wettability.

A 'negative' pattern (holes in a polymer film) can be prepared by adding PMMA to the PS ethyl acetate solution. The gelation and phase separation leads to a PMMA film with dispersed PS islands. Those islands can be selectively dissolved by using cyclohexane. Both patterns, the 'positive' PS islands as well as the 'negative' PMMA porous films can

be sued as etching masks for patterning of silicon wafers for solar cell applications, because the increased surface roughness decreases back reflection.

The materials used for the pattern formation are all commercially available, low cost and environmentally friendly. The patterns are produced by a cost-effective coating techniques and thus are promising candidates for commercialization.

References

Kiyono Yuji, Olaf Karthaus e-J. Surf. Sci. Nanotech., 9, (2011) accepted

8438-11, Session 3

Light trapping in thin film solar cells: towards the Lambertian limit

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Prospects for large-scale applications of solar cells will depend to a large extent on the development of low-cost, high-efficiency photovoltaic (PV) devices that use a reduced amount of semiconductor material. Thin-film solar cells based either on silicon (crystalline, micro-crystalline, amorphous) or on compound semiconductors (CdTe, CIGS) are especially promising, but in order to increase the absorption of light in a thin semiconductor layer (from 1-2 microns to a few hundreds of nanometers or even below) and to enhance the energy conversion efficiency, appropriate light-trapping schemes must be used. While light trapping in wafer-based solar cells is well known from geometrical optics [1,2] and it has an ultimate limit which corresponds to an enhancement of the light path by a factor 4n2, where n is the material refractive index, the maximum light trapping enhancement in thin-film solar cells with a film thickness of the order of the wavelength of light - and the best structures to achieve it - are just starting to be investigated [3,4].

In this work we theoretically investigate the light trapping properties of one- and two-dimensional periodic patterns etched in crystalline and amorphous silicon solar cells with anti-reflection coating and back-reflector, in a wide range of active material thicknesses. The resulting short-circuit current (taken as the figure of merit for efficiency) and the optical spectra are compared with those of an unpatterned cell, and with the ultimate limits to light trapping in the case of a Lambertian (isotropic) scatterer. Photonic patterns are found to give a substantial absorption enhancement, especially for two-dimensional patterns and for thinner cells, thanks to physical mechanisms like reduction of reflection losses, diffraction of light into the cell, and coupling into the resonant optical modes of the structure. While the present results clarify the expected increase of light absorption by periodic photonic lattices, further improvements are expected by optimizing the anti-reflection properties and by employing more advanced (e.g., disordered) photonic structures.

[1] E. Yablonovitch, J. Opt. Soc. Am. 72, 899 (1982).

[2] M. A. Green, Progr. Photovolt.: Res. Appl. 10, 235 (2002).

[3] Z. Yu, A. Raman, and S. Fan, Optics Express 18, A366 (2010).

[4] S. Zanotto, M. Liscidini, and L.C. Andreani, Optics Express 18, 4260 (2010).

8438-12, Session 3

Simulation of light-trapping in thin film solar cells by high-performance computing

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A sophisticated light management is important to construct thin-film solar cells with optimal efficiency. The light management is based on suitable nanostructures of the different layers and materials with optimized optical properties. To design thin-film solar cells with high efficiency, simulation of light trapping is a very helpful tool. Such a simulation has to take into account the underlying physical effects like plasmonic effects of silver or interference effects. To this end, it is important to solve Maxwell's equations on a discretization grid. To obtain an accurate simulation, the roughness of the top TCO layer is decribed by AFM-scan data. To meet the high computational amount in solving Maxwell's equations on a finite difference discretization grid, high performance computers are used.

8438-13, Session 3

Light harvesting schemes in thin film silicon solar cells

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To further enhance the potential of thin-film silicon solar cells, efficient light harvesting schemes are essential. Reflection and parasitic absorption losses must be minimized, while efficient light trapping in the cell is crucial to keep thin absorber layers; typically below 300 nm in amorphous silicon (a-Si:H) to limit light induced degradation of the cell electrical properties, and below 2 µm for micro-crystalline silicon (µc-Si:H) to limit production costs. Very importantly, the light harvesting techniques must not impact the cell electrical performance. For high efficiency TF-Si devices, the a-Si:H/µc-Si:H tandem configuration is used: light harvesting has thus to be realized in both sub-cell while guaranteing surface morphologies adapted to the growth of high quality silicon layers. Cell design and superstrates developed in our laboratory to allow for high optical and electrical performances will be presented.

The excellent light scattering and transparency provided by randomly textured ZnO electrodes grown by low pressure CVD (LPCVD) will be reviewed. In addition, we will show that arbitrary textures from master materials can be transferred directly to ZnO electrodes via a nanomoulding technique, or onto a transparent lacquer via nanoimprinting lithography. To minimize parasitic absorption and to selectively reflect light between the top and bottom cells, nanostructured doped silicon rich silicon oxide materials will be presented. They will be shown to improve the cell resilience to the substrate roughness, enabling the integration of more agressive light trapping schemes. Finally, multi-scale textured superstrates will be shown: small features of a thin LPCVD ZnO layer are combined with nanoimprinted large features, resulting in currents higher than 28 mA/cm2, for a cell initial efficiency of 14.1 %.

Various ways of integrating advanced nanostructured materials into high-efficiency thin-film silicon solar cells will therefore be presented, opening more effective light trapping opportunities.

8438-14, Session 3

Comparison of periodic and random structures for scattering in thin film crystalline silicon solar cells

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Compared to other thin-film materials like CdTe or CIGS, crystalline silicon is a very weak absorber. For this reason, light trapping is of key importance for thin-film crystalline silicon solar cells. One way to achieve light trapping is by incoherent scattering or diffraction. With incoherent scattering, a maximum absorption enhancement corresponding to the Yablonovitch factor of 4n2 (roughly 50 for silicon) is possible [1], independent of the incident spectrum. For diffraction even greater absorption enhancement is possible [2], but is limited to a certain spectral range.

The absorption coefficient of silicon is high for photons in the blue part of the spectrum but decreases towards smaller photon energies. The spectral range, in which light trapping is required, is therefore limited to photons with energies close to the band gap. The width of this spectral range depends on the thickness of the absorber. The situation becomes even more complex when taking into account that, in praxis, the scattering abilities of a certain texture are limited by what kind of texture features can be realized in a certain texturing process. Given these reasons, it is hard to tell if a periodic structure to induce coherent scattering can outperform a periodic structure. This question becomes even more difficult, when taking into account that the fabrication process for a periodic structure will be more complex and therefore more costly than that for a random texture.

In this study we compare the light trapping induced into crystalline silicon thin-films by periodic and random structure with realistic geometries. Realistic geometries are obtained by investigating fabricated textures and analyzing the occurring surface geometries. To evaluate the structures, electrical and optical simulation methods are combined to calculate the electrical characteristics of a thin film solar cell. The solar cell efficiency is used as a figure of merit.

[1] Yablonovitch E. J Opt Soc Am 1982; 72: 899-907

[2] Yu Z, Raman A, Fan S. Opt Exp 2010; 18: A366-A380.

8438-15, Session 3

Optimization of thin film amorphous silicon solar cells using rigorous electromagnetic simulation techniques

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Thin-film amorphous silicon based solar cells are an attractive design for providing cost-effective and efficient solar energy. Amorphous hydrogenated silicon (a-Si:H) can be deposited in thin layers on cheap substrate materials such as glass or plastic offering low fabrication costs suitable for mass production. One of the major barriers to the widespread use of a-Si:H solar cells is their increased defect density under light exposure - the Staebler-Wronski (SW) effect.

To mitigate (SW) effects, low thickness absorber layers (in the range of a few hundred nanometers) that exhibit a high electric field are typically employed. Considering the large absorption length of amorphous silicon near its bandgap, these thicknesses necessitate light-trapping concepts for realizing efficient thin-film silicon solar cells.

Within this work, we numerically optimize the light trapping efficiency of a periodic, wavelength-scale structured back metal contact by rigorously solving Maxwells'equations over a wide range of geometry parameters. Our model (p-i-n type) solar cell consists of a nano-structured silver back contact deposited on a plastic substrate, followed by 50 nm of Al:ZnO, 200 nm of a-Si:H and a final layer of tin doped indium oxide. The nano-structured back contact effectively increases the light path in the absorber by (i) exciting photonic waveguide modes in the absorber and (ii) coupling incident photons to surface plasmon polaritons (SPPs).

For each set of geometry parameters, we simulate the 3D wave propagation inside the solar cell by solving Maxwells' equations in the frequency domain for a frequency range of 350 to 900nm using the finite element method. Based on the electric field in the absorber layer we compute the short circuit current density in order to compare the efficacy of different light trapping geometries.

In using our optimization approach we have identified nanostructure back reflector geometries that display a 50% increase in short circuit current density over flat back reflectors.

8438-16, Session 4

Nanostructured micron-thin crystalline-silicon solar cells: towards tailored and integrated light-management schemes

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No abstract available

8438-17, Session 4

Influence of texture modifications in silicon solar cells on absorption in the intrinsic layers

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In thin-film silicon solar cells, textured transparent conductive oxides (e.g. ZnO:Al) are commonly used as front contact to improve light absorption due to light scattering. These textures can be achieved in multiple ways, for example by ion beam treatment, wet-etching and nano-imprinting. In our case, the focus lies on the latter two.

We have investigated the influence of different artificial textures on the absorption in amorphous silicon (a-Si:H) single junction and a-Si:H/microcrystalline silicon tandem solar cells using finite-difference time-domain simulations. The simulations cover the typical spectral range of operation of the cells , i.e. 350nm-800nm for the a-Si:H single junction device and 350nm-1100nm for the tandem device. The investigations are based on a ZnO-layer which was wet-etched in diluted hydrochloric acid for 50s. Several modifications of this surface were considered, including various device and backside material configurations. For all configurations, the absorption in the intrinsic layers is compared to a device based on the original texture. Using these modifications, the influence of local features on absorption is considered, taking into account height, size and shape of the feature in question. The following questions will be addressed: Is the absorption influenced by local features or overall distribution of features? What feature sizes dominate the effects (height, size, shape or a combination of these)? What are the optimal features for each device type? Is it possible to create an optimal structure to obtain a maximum increase in absorption? The last question is of importance especially in regard to nano-imprinting processes, since nano-imprinting will make it possible to create a device based on the optimal simulated texture and to compare simulation results with real-world devices.

8438-18, Session 4

Intermediate and backside reflectors in thin film silicon solar cells based on 3D photonic crystals

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Unbalanced currents in serial-connected tandem solar cells are one of the major limitations for cost-efficient fabrication of third generation solar cells. By using optimized photon management, we will show for a micromoph solar cell that an embedded 3D photonic crystal acting as an intermediate reflector can balance the currents. It enhances experimentally the external quantum efficiency (EQE) for the current-limiting top cell up to factor of 3.6 corresponding

to a short circuit current enhancement of about 25 % as compared to state-of-the-art textured micromorph solar cells. Moreover, the concepts of this intermediate reflector has also been extended on flexible substrates for backside reflectors.

8438-19, Session 4

Photocurrent enhancement with photoemission from metal nanoparticles

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Harvesting of solar energy is considered widely as an important future green power generation technology. However, high cost of photo-generated electricity, related to high cost of the photovoltaic module production in comparison to their efficiency, has to be reduced before we can achieve the large-scale exploitation of solar energy.

Addressing this issue, we consider a possibility of increasing photocurrent in solar cells using the electron photoemission from small metal nanoparticles into a semiconductor, which can result from absorption of photons and generation of Local Surface Plasmons (LSP) in the nanoparticles with optimized geometry.

We study the effect on a model system, which is a Schottky barrier n-GaAs solar cell, with an array of metal nanoparticles incorporated into the Schottky contact. We use numerical simulations to design the metal nanoparticle array in order to tune the LSP resonance to the wavelength corresponding to the energy below the bandgap of GaAs. A photocurrent induced by such resonances adds to the diode photocurrent and thus extends spectral response range of the device. The theoretical model shows that resonances can be tuned with the shape, dimensions, aspect ratio and period of the embedded nanoparticles.

Based on the simulations, we fabricate devices with Au nanoparticles of circular or rectangular shape, with dimensions ranging from 30nm to 100nm deposited on the surface of n-GaAs and under a 100nm layer of a ITO Schottky contact. The geometry of the nanoparticles is set by the need to maximize the electric field at the interface with the semiconductor, leading to a strong electron photoemission into the semiconductor. Such devices are then assessed by comparing their spectral response with those of reference devices without nanoparticles. Results of electrical measurements are further compared with optical characterization of LSP in order to provide full analysis of photoemission.

8438-20, Session 5

Optimal antireflective design for light harvesting in silicon nanowire solar cells

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Surface antireflection techniques adopting nanostructures are of considerable importance for achieving high photovoltaic performances while effectively reducing the light reflection in crystalline Si solar cells. Subwavelength Si nanostructures have been increasing interest owing to their unique optical properties such as superior antireflection characteristics and omnidirectional light absorption over a broad wavelength range at various angles of incidence. In particular, Si nanowire (SiNW) arrays which have ultralow reflection exhibit the potential to be used as antireflection coating in solar cells. Since the most recent works focused only on the optical characterization without serious considerations of a carrier collection efficiency, it is a still open question for a possible use in practical solar cells. Improved light absorption while avoiding degradation in electrical parameters is of critical importance for obtaining a high efficiency in SiNW solar cells.

In this talk, a design guideline which optimally combines light absorptance and electrical performances is proposed using a tradeoff relation between wire lengths and their space filling ratio. Superior antireflection characteristics of a SiNW array are understood using two distinctive features such as multiple scattering and reduction of a refractive index mismatch. In addition, further integration using ZnSe quantum dots (QDs) onto the SiNWs presents considerable enhancement in external quantum efficiency over a broadband range owing to two major benefits, i.e., light trapping and photon down-conversion. Superior antireflection characteristics obtained using ZnSe QDs is also effective because the wire length required for obtaining the efficient light absorption can be decreased to suppress the recombination loss.

8438-21, Session 5

Black silicon photovoltaics

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The challenge of future solar cell technologies is the combination of highly efficient cell concepts and low cost fabrication processes. A promising concept for high efficiencies is the usage of nanostructured silicon, so called black silicon. Due to its unique surface geometry the optical path of the incoming light through the silicon substrate is enhanced to nearly perfect light trapping.

Combined with the semiconductor-insulator-semiconductor (SIS) solar cell concept it is possible to fabricate a low cost device by using conventional sputtering technologies. Therefore, a thin insulator is coated on the nanostructured silicon surface, followed by the deposition of a transparent conductive oxide (TCO), e.g. indium tin oxide (ITO) or aluminum doped zinc oxide (AZO). In such systems the TCO induces a heterojunction, hence, high temperature diffusion processes are not necessary.

The optical and geometrical properties of different nanostructured silicon surfaces will be presented. Furthermore, the influence of the used TCO materials will be discussed and the solar cell performance under AM1.5G illumination of unstructured and structured SIS devices is shown.

8438-22, Session 5

Nanostructured black silicon anti-reflection in both high-current photocathodes for hydrogen production and 18.2%-efficient photovoltaics

H. M. Branz, T. G. Deutsch, H. Yuan, J. Oh, National Renewable Energy Lab. (United States)

One-dimensional (1-D) silicon nanostructures can provide good performance as photocathodes for solar hydrogen production because of their excellent anti-reflection (AR) properties and high surface area. They can also function as AR coatings on highly-efficient photovoltaic (PV) cells if nanostructure surface and doping densities are well-controlled. Our nanostructured black silicon is fabricated by simple metal-assisted etching techniques, and consists of vertically aligned nanopores of random depths of more than 300 nm, and with feature sizes smaller than about 50 nm.

By using black Si to reduce reflection without the need for an insulating AR coating, we have fabricated photocathodes for water splitting that provide approximately 20 % increase in the rate of solar hydrogen production compared to planar Si. The nanostructured photocathodes also facilitate H_2 bubble evolution and reduce the overpotential required for the water-splitting half-reaction by increasing the surface density of reaction sites. Recently, we have begun applying catalysts to the surface nanostructures of black Si p/n junctions to further reduce the overpotential.

We have also fabricated an 18.2%-efficient (confirmed, 1 sun, AM1.5) nanostructured black Si solar cell without any additional AR coating, which we believe to be the most efficient solar cell with intentional nanostructuring. Our nanostructured solar cells have a density-graded layer that reduces the reflection of silicon in air to below 4% across the usable solar spectrum with λ <1.2 μm. Black silicon can therefore provide high solar conversion efficiency, while significantly reducing manufacturing costs by eliminating the industry-standard SiNx AR coatings. However, increased photocarrier recombination in 1-D nanostructures can limit the spectral response at short wavelengths in PV and cells. We present novel processing schemes that enable us to control both surface and emitter Auger recombination mechanisms in the nanostructures.

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8438-23, Session 5

Analysis of surface recombination in nanowire array solar cells

S. Yu, F. Roemer, B. Witzigmann, Univ. Kassel (Germany)

Nanowire arrays feature unique advantages when applied to photovoltaics. Due to an optical micro concentration effect, the absorption of nanowire arrays is comparable to that of conventional solar cells yet with much less material use. In addition, the lateral relaxation of built-in strain of a single nanowire enables flexible selection of materials to match the optimum bandgap combination for multi-junction solar cells. Thus nanowire array solar cell is a viable technology for 3rd generation photovoltaics.

The theoretical efficiency limit can be evaluated by the widely accepted Shockley-Queisser method. The Shockley-Queisser model considers radiative recombination, however for a more accurate approach to calculate the solar cell efficiency, non-radiative recombination should be included. Surface recombination is a major concern due to the large surface to volume ratio of nanowire array solar cells.

In this work, microscopic three-dimensional simulations have been performed on both axial and core-shell nanowire array solar cells by solving the continuity equations together with a Poisson equation. Surface recombination was included in our simulation by applying the Darling model; radiative recombination, Shockley-Read-Hall recombination and Auger recombination mechanisms were also included. The optical generation is obtained by solving 3D Maxwell equations. Two recombination velocities were taken to cover the possible range of surface recombination strength: 1e3cm/s and 1e6cm/s.

The Shockley-Queisser limit of a sparse InP nanowire array solar cell is around 30%, which is similar as that of thinfilm solar cell. Results calculated by microscopic carrier transport model show that with low surface recombination velocity (1e3cm/s), the nanowire solar cells' performance is barely affected. With the inclusion of stronger surface recombination (1e6cm/s recombination velocity), the efficiency of axial nanowires drops by 63.2%, while the efficiency of core-shell nanowires drops by 24.1%. While the reduction of short circuit current and open circuit voltage occurs in both structures, the axial structure suffers from a substantial efficiency loss.

The explanation can be given by the analysis of internal device physics, in particular the local surface recombination rates within the two structures. When applied with same doping density and surface recombination velocity, the surface recombination rate in the core-shell structure is lower due to lower surface minority carrier concentration, which is introduced by the proximity of the p-n junction to the nanowire surface. This results in better tolerance for surface recombination. A very obvious shrink down of active region volume occurs in the axial structure due to the strong surface recombination (1e6cm/s case), leading to the decrease of both short circuit current and open circuit voltage.

8438-24, Session 5

Electron recombination dynamics in CdSe/ P3HT hybrid heterojunctions

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The combination in hybrid heterojunction of nanocrystals and semiconductor polymers has great potential for light-to-energy conversión devices. For this reason, a great number of different quantum dots/polymer molecular solar cells have been investigated. However, less attention has been paid to the photo-induced charge transfer processes in the interface of these systems. Here we report a detailed time resolved spectroscopic study of hte most important electron transfer steps of CdSe/P3HT bulk heterojunction films. From the data obtained using Time Correlated Single Photon Counting we have inferred that electron injection from P3HT excited state to CdSe conduction band occurs faster tan 250 ps and the electron yield is higher tan 90%. On the other hand, the use of Laser Transient Absorption Spectroscopy allowed us to observe that all the studied interfacial charge transfer process can be fotted to dispersive stretched exponentials kinetics, independently of the QD's concentration, thereby offering evidence of multiple decay process in CdSe/P3HT solar cells.

8438-25, Session 6

Photon management structures for solar cells

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Since micro- and nanostructures for photon management are of increasing importance in novel high-efficiency solar cell concepts, structuring techniques with up-scaling potential play a key role in their realization. Interference lithography and Nanoimprint processes are presented as technologies for origination and replication of fine-tailored photonic structures on large areas.

At first, these structure origination and replication technologies are presented in detail: With the interference pattern of two or more coherent waves, a wide variety of structures with feature sizes ranging from 100 nm to 100 μm can be generated in photoresist. Examples are linear gratings (two wave interference), crossed gratings (combination of two exposures, each with two waves), hexagonal structures (three wave interference), three dimensional photonic crystals (four wave interference) or surface-relief diffusers (multi wave interference). The strength of this technology is that homogeneous structures can be originated on areas of up to 1.2 x 1.2 m². The structures in photoresist, the so-called master structures, can serve as an etching mask for a pattern transfer, as a template for infiltration with different materials or they can be replicated via electroplating and subsequent replication processes such as nanoimprint lithography (NIL). Especially in combination with replication steps, the industrially feasible production of elaborate structures is possible.

After the description of the basic technologies, four application examples for solar cells are presented with details about the design of the structures, the structuring processes, sample characterization and evaluation:

(1) honeycomb structures for the front side texturization of multicrystalline silicon solar cells

(2) diffractive back side gratings for absorption enhancement in the spectral region near the band gap of silicon

(3) periodic and aperiodic imprinted structures as substrates for TCO deposition

(4) plasmonic metal nanoparticle arrays manufactured by combined imprint and lift off processes

8438-26, Session 6

Enhanced light trapping in crystalline silicon solar cells by nanoimprint lithography

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In order to compensate for the loss in light absorption due to the thinning down of crystalline silicon photoactive layers, highly efficient light-trapping should be achieved. It has been shown theoretically that periodic nanostructures can achieve an absorption enhancement surpassing the limits of random Lambertian structures [1]. In this study, 2D photonic nanostructures are fabricated by soft nanoimprint lithography (NIL) [2]. NIL is a recent, emerging and single-side top-down approach which allows fabricating nanometer scale patterns. It is being increasingly used in various fields, including photonics, but it has been barely investigated for light trapping in crystalline silicon solar cells. The aforementioned 2D photonic nanostructrures act as diffraction gratings by exploiting the wave nature of light and can be fabricated by NIL on either side of crystalline silicon. When fabricated on the front side, they additionally result in a graded index antireflection behavior. Apart from the light manipulation, they also cause a significantly lower material loss compared to conventional texturing techniques since less than a micron of silicon is consumed. Therefore, they could be integrated in ultra-thin cell technologies enabling their fabrication, boosting their efficiencies and achieving cost reduction. 2D periodic nanopatterning by NIL was applied to various crystalline silicon cell technologies, both on foreign substrates and wafer-based, with thicknesses ranging from 1 to 180 µm. An absorption enhancement within the whole range of wavelengths has been obtained for a front-side nanopatterned 1 µm epitaxy-free [3] monocrystalline silicon film compared to the unpatterned epifree film. The absorption reached values of 80% for short wavelengths. The enhancement was six-fold for wavelengths above 800 nm, reaching more than 60% of absorption. The overall absorption was similar to that of an equivalent effective thickness of around 40 µm. For a 3 µm thick polycrystalline silicon layer, with a grain size of around 15 µm, enhanced absorption compared to the unpatterned case has been obtained when NIL was performed on the front side. The result is competing with the currently used random plasma texturing with similar material loss. On the other hand, an absorption enhancement has been obtained when the nanopatterning was performed on the back side of 180 µm wafers, thus, exploiting the long wavelengths above 1000 nm. The results were verified though simulations based on the resolution of Maxwell's equations in the transfer-matrix formalism. Finally, the integration of such nanostructures in existing solar cell fabrication process flows will be shown. There will be particular focus on the effect of passivation so as for the absorption enhancement to be effectively translated into increased electrical conversion efficiency.

References:

[1] Mellor A. et al., "Upper limits to absorption enhancement in thick solar cells using diffraction gratings," Progress in Photovoltaics: Research and Applications 19(6), 676-687 (2011).

[2] Younan Xia and George M. Whitesides, "Soft lithography," Annual Review of Materials Science 28(1), 153-184 (1998).

[3] Depauw V. et al., 'Epitaxy-free monocrystalline silicon thin film: first steps beyond proof-of-concept solar cells', Progress in Photovoltaics: Research and Applications 19(7), 844-850 (2011).

8438-27, Session 6

Preparation of periodically arranged metallic nanostructures using nanoimprint lithography

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Plasmonic effects are of increasing interest for photon management in solar cells [1]. Two promising concepts are light trapping and enhanced upconversion through scattering/diffraction and plasmonic resonances on metallic nanoparticles.

The main challenge is the production of defined periodic structures on large scales. In literature examples are given of aperiodic nanoparticles produced by heating a metal layer [2]. The typically used techniques for fabrication of ordered structures are based on lithographic methods. Most of these techniques are restricted to small areas (e.g. e-beam lithography). For our process chain we use interference lithography for master production and nanoimprint lithography (NIL) for replication [3]. The advantage of using interference lithography is the possibility to texture large areas and the variety of geometries, shapes and arrangements. It is possible to manufacture 1D (e.g. line gratings), 2D (e.g. cross gratings) or 3D (e.g. photonic crystals) structures on areas of up to one square meter with different numbers and arrangements of beams.

In a first step a master is produced using interference lithography. From the master a silicone stamp is molded. The stamp is then used to transfer the pattern into a resist by printing and subsequent curing under UV light. To remove the residual resist layer, the substrate is plasma etched prior to the next step. Thereafter, the whole sample is metallized. The last step is the lift off of the resist, resulting in nanoparticles on the sample surface. The advantage of this process is the flexibility of structure size, shape and arrangement in combination with easy to handle materials for large scale application in solar cell production.

We show results received by using the above mentioned process to prepare defined periodic plasmonic nanostructures on glass substrates and silicon wafers. The samples are characterized and results are compared to wave optical simulations.

References

[1] H.A. Atwater and A. Polman, Nature Materials, 9, 205-213, 2010

[2] S. Pillai et al, J. Appl. Phys., 109, 073105, 2011

[3] B. Bläsi et al., Proc. 26th EU-PVSEC, Hamburg, 2011

8438-28, Session 6

Thin film surface processing by ultrashort laser pulses (USLP)

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In this work, we study the feasibility of surface texturing of thin molybdenum layers on a borosilicate glass substrate with Ultra-Short Laser Pulses (USLP). Large areas of regular diffraction gratings are produced consisting of Laser Induced Periodical Surface Structures (LIPSS).

A short pulsed (230fs-10ps) laser was applied using a focused Gaussian beam profile (15-30µm). In addition, laser parameters such as fluence, overlap and overscans, repetition frequency (100-200kHz), wavelength (1030nm, 515nm, 343nm) and polarization are varied to study the effect on periodicity, height and especially regularity of LIPSS obtained in layers of different thicknesses (150-400nm). Aim is to produce these structures without cracking the metal layer and with as little as possible ablation.

It was found that USLP are suitable to reach high power densities at the

surface of the layers, avoiding mechanical stresses and cracking, which are a critical issue during thin films processing.

A possible PV application could be found in texturing of thin film cells to enhance light trapping mechanisms.

8438-29, Session 6

Investigation of CIS/CIGS and CdTe solar cells scribing with high-power fibre short pulse lasers

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The European project ALPINE is dedicated to the determination of the ideal laser parameters for solar cells scribing and the development of optimized fibre laser sources.

In this paper we would like to present the results obtained with different pulses duration and repetition rate for the scribing of thin-film CIGS and CdTe solar cells.

Subsequently a fully fibred laser system has been developed. The laser is based on a MOPA configuration. An externally modulated laser diode is used a seed source. This diode produces adjustable pulses from 200 ps to 7 ns.

The diode is amplified up to 2 Watts though various all-flexible-fibre amplification stages. The spectral linewidth of the laser is 0.05 nm. The amplification is limited to 2 Watts only for the longer pulses duration due to Stimulated Brillouin Scattering non-linear effects.

The last amplification stage is based on a straight rod-type fibre. The maximum power at the output of this high amplification stage ranges from 17 to 25 W depending on the pulse duration, at 500 kHz repetition rate and the resulting in an energy per pulse of 34 to 50 µJ.

For the shorter pulses the peak power reached 170 kW. No trace of spectral broadening and self-phase modulation have been observed up to this power level.

The laser has been frequency doubled and used in a 2D scribing system. More results in the femto-pico regime have been obtained with other laser sources and are used for comparison.

8438-30, Session 7

Advanced resonance-shifting approaches to increase the efficiency of luminescent concentrators

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Luminescent solar concentrators (LSCs) were developed over three decades ago as a simple route to obtain high concentration ratio for photovoltaic cells without tracking the sun. These devices traditionally consist of a transparent slab embedded with a chromophore that absorbs sunlight and re-emits it back into the slab, where it is trapped by total internal reflection, transported through the slab, and subsequently absorbed by photovoltaic cells attached to the edges. Concentration ratios exceeding 100 are theoretically possible, however, in practice, the overlap between chromophore absorption and emission spectra ultimately leads to unacceptable reabsorption losses that limit the concentration ratio to ~10, and hence the utility of LSCs to date.

Recently, we have developed an all-optical means of overcoming the reabsorption problem by incorporating a simple bilayer cavity on top of a transparent substrate and continuously varying its resonance (i.e. thickness) across the lateral dimensions of the concentrator. In this ‘resonance-shifting’ approach,[1] sharply directed emission from the cavity continuously avoids the narrow reabsorption resonance at each subsequent bounce and hence propagates with low loss to the substrate edges. Here we extend these results through a series of ray tracing simulations to evaluate and optimize alternative resonance-shifting strategies such as shaped substrates with a slowly varying surface profile, as well as others that feature graded refractive index variation. We find that certain designs lead to repulsive optical potentials that naturally drive light from the center toward the concentrator edges, thereby furthering the performance improvement gained by resonance-shifting and at the same time simplifying device fabrication.

1. N.C. Giebink, G.P. Wiederrecht, and M.R. Wasielewski. Nat. Photon. 5, 694 (2011)

8438-31, Session 7

New low-cost high-efficiency solar module: diffracting deflector module

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New low cost, high efficiency solar module: Diffracting Deflector Module

Solar industry needs to increase solar panel efficiency, by improving solar cells and solar modules. This industry also needs to be cheap in order to compete with the other energies. To achieve both goals we have developed a new kind of module using diffraction gratings in order to deflect sunlight on a solar cell. Diffraction gratings can be used for many means, such as anti-reflect or self cleaning layers [1] [2] [3] [4]. We describe here the use of diffraction gratings as concentrators. The same kind of method has been used industrially by Prism Solar to increase the efficiency of solar panels, but using holographic gratings whereas we use surface gratings on the glass cover. We have proceeded to simulations to design the submicrometric diffraction grating, in order to deflect a much light as possible, within a selected wavelength range. To achieve this optimized design, we have developed a cheap process combining fast direct writing and cheap materials, making this process industrially valid. The dynamical interferometric lithography [5] [6], developed at the Laboratoire Hubert Curien (LaHC) in Saint Etienne (France), is a technology dedicated to the fabrication of diffraction gratings, using an interferogram produced by a laser through a phase mask. The technique allows us to write a pattern directly on a substrate. We have used a sol-gel process [7], developed in the Laboratoire des Matériaux et du Génie Physique (LMGP) in Grenoble (France), in order to produce a photopatternable amorphous TiO_2 xerogel thin film, which after thermal treatment becomes crystalline titanium dioxide. Both techniques are compatible with large surface processing.

We present here the parameters and the optimizations of the diffraction gratings and the first results about the benefits of such panels. We will also deal with the potential of these modules and the perspectives in order to improve them.

1. J. Chen, Q. Wang, et H. Li, “Microstructured design of metallic diffraction gratings for light trapping in thin-film silicon solar cells,” Optics Communications 283, 5236 -5244 (2010).

2. C. Heine et R. H. Morf, “Submicrometer gratings for solar energy applications,” Appl. Opt. 34, 2476-2482 (1995).

3. H. Stiebig, C. Haase, C. Zahren, B. Rech, et N. Senoussaoui, “Thin-film silicon solar cells with grating couplers - An experimental and numerical study,” Journal of Non-Crystalline Solids 352, 1949-1952 (2006).

4. J. E. Ludman, “Holographic solar concentrator,” Appl. Opt. 21, 3057-3058 (1982).

5. E. Gamet, Y. Jourlin, S. Pelissier, R. Min, S. Reynaud, C. Veillas, J.-C. Pommier, et O. Parriaux, “Flying phase mask for the printing of long submicron-period stitchingless gratings,” Microelectronic Engineering 83, 734-737 (2006).

6. P. Müller, Y. Jourlin, C. Veillas, G. Bernaud, Y. Bourgin, S. Tonchev, et O. Dellea, "On-the-fly writing of a long grating phase mask," Optical Engineering 50, 038001 (2011).

7. S. Briche, Z. Tebby, D. Riassetto, M. Messaoud, E. Gamet, E. Pernot, H. Roussel, O. Dellea, Y. Jourlin, et M. Langlet, "New insights in photo-patterned sol-gel-derived TiO2 films," J Mater Sci 46, 1474-1486 (2010).

8438-32, Session 7

Light-guide-based diffractive solar concentrators

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Conventional solar concentrators can achieve high concentration ratios, but are often large, heavy and relatively expensive. Therefore, a system that achieves a low concentration ratio, but which is inexpensive, flat and lightweight can be an interesting alternative. We study the design of a compact solar concentrator which is based on diffraction. Incident sunlight is diffracted into a light guide by transmission gratings and then guided towards a solar cell via total internal reflection (TIR). Diffracting light into TIR requires gratings that combine a large diffraction angle with a high diffraction efficiency, preferably over a broad range of incident angles and wavelengths. We discuss the design of gratings with these properties and show how one can control their angular acceptance. To this end, we consider surface-relief gratings with sub-wavelength periods and use Rigorous Coupled-Wave Analysis for a numerical study of their diffractive properties. It is found that, for a well-chosen grating thickness, there are specific regions in the full space of conical angles of incidence where light is efficiently diffracted into TIR. The location of these regions depends on the characteristics of the grating, like its refractive index and its topological symmetry. Gratings with a high refractive index have a broader angular acceptance. For slanted gratings the efficiency regions corresponding to positive orders are promoted at the cost of those corresponding to negative orders or vice versa. For two-dimensional, crossed gratings the diffraction efficiency has lower peak values, but is also less dependent on the angle of incidence. As a consequence, one can select either a narrow range of incident angles for which the diffraction efficiency is very high, or a more uniform distribution of the diffraction efficiency over a wide range of incident angles by choosing appropriate grating parameters. Our numerical predictions are supported by measurements on holographic surface-relief gratings. We used the photoresist SU-8 to show that gratings with the desired dimensions can be fabricated by interference holography and demonstrated the desired properties. Finally, we discuss the application of gratings in a concentrator system. Diffractive solar concentrators are subject to the brightness theorem and the concentration ratio will depend on the geometrical design of the complete system. We will consider the resulting limitations and possibilities in designing diffractive solar concentrators.

8438-34, Session 7

Neodymium-doped glasses as fluorescent concentrators for the infrared spectral range

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Fluorescent concentrator systems offer a highly efficient use of sunlight in a relatively small spectral range. In their working range they absorb the incident sunlight and convert it to light of longer wavelengths. The emitted light is then guided to the edges of the fluorescent concentrator plate which are optically coupled to a solar cell optimized for the spectral range of emission. However, so far efficient fluorescent concentrators are only available for the visible spectral range. Neodymium-doped glasses are regarded as promising concentrator materials for the infrared spectral range. The optical properties of Nd3+-doped barium borate and fluorozirconate glasses have been investigated. Borate glasses are good candidates as matrix materials since they are robust, inexpensive and offer a high optical transparency. Fluorozirconate glasses, however, provide high fluorescence intensities due to their low phonon frequencies.

Additional doping of the glasses with silver oxide and performing subsequent heat treatment causes the reduction of the doped silver ions leading to the metallic silver nanoparticles. The idea is to enhance the fluorescence intensity significantly by local field enhancement around the Nd3+ ions due to surface plasmons from silver nanoparticles in close proximity. We investigated the growth of silver nanoparticles for different heat treatment protocols and the effect of the local field enhancement on the fluorescence intensity.

8438-36, Session 7

Planar lightguide solar concentrator

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Solar concentrators can provide high light concentration ratio by collecting sunlight of large area to a smaller light-receiving region of high-efficiency photovoltaic (PV) cell. Using solar concentrators in photovoltaic systems shows great potential in getting higher overall energy conversion efficiencies and lower costs. The planar lightguide solar concentrator has attracted many attentions for its promising for thin form-factor, lightweight, and inexpensive replacements for the current generation of refractive and reflective solar concentrators. The key problem to solve while designing a planar lightguide solar concentrator is preventing sunlight leakage from a planar solar concentrator while maintaining its high light concentration ratio.

This study proposes a new type planar lightguide solar concentrator, which collects vertically incident sunlight of large area to one lateral surface of the planar lightguide of much smaller area. Simulation results shows that the planar lightguide solar concentrator can achieve 98.8% and 97.5% optical efficiency at 100× and 225× concentration ratio, respectively (The results excludes the Fresnel loss of each surface). The proposed planar lightguide solar concentrator consists of a two-dimensional lens array and a planar prism array lightguide, where the prism array planar lightguide comprise several micro structures and a suitable organized prism structure array. In this design, the incident sunlight is collected by each lens in a two-dimensional lens array and is coupled into a prism array planar lightguide using localized micro structure placed at each lens focus. The prism structure and the micro structure are organized in a way that the side surfaces of the prism structure and the micro structure are parallel to each other. With the structure arrangement, the coupled sunlight in the lightguide could be successfully guided to one lateral surface of the planar lightguide of much smaller area while preventing most of light leakages form the planar lightguide.

8438-46, Session 7

Broadband excitation of upconversion in lanthanide doped fluorides for enhancement of Si solar cells

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The use of upconverters (UC) to harvest light with photon energy below the bandgap of the cell is one possible route to overcome the

Shockley-Queisser limit for single junction cells. The materials which have shown the greatest potential in this area are lanthanide ions such as erbium (Er^{3+}) whose UC mechanism is non-linear with incident power. In addition, the UC has a low absorption cross section over a narrow bandwidth which significantly reduces its efficiency. Erbium based UC has been studied extensively, but predominantly for monochromatic excitation, since it presents an energy ladder with almost equal spacing (~6500 cm-1), with the peak resonant wavelength absorption of the UC at 1523nm. This wavelength has been proved to be the most efficient at achieving NIR UC although the material responds to light in the range of 1480nm-1580nm. As mentioned, the response of the material is non-linear and hence by increasing incident power will lead to a higher UC efficiency. This means that broadening the spectral content of the excitation source will lead to a higher photon density without a relative increase in solar irradiance. Furthermore as their application will be for concentrated PV application it is important to understand their performance under broadband irradiance. In this paper, we will discuss the experimental set-up and characterisation of a supercontinuum (SC) LASER and a high power acousto-optical tunable filter (AOTF-HP) used as a broadband excitation source. In this configuration, the UC emission can be measured under a single channel (~10nm bandpass) of excitation or up to 8 channels simultaneously, meaning excitation of almost the full Er^{3+} absorption range. Initial results of the effect on UC emission for oxyfluoride transparent glass ceramics with embedded Er^{3+} doped YF_3 nanocrystals will also be presented.

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8439-01, Session 1

Characterization of fiber Bragg grating-based sensor array for high-resolution manometry

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The combination of fiber Bragg grating arrays integrated in a soft plastic tube is promising for high resolution manometry (HRM) where pressure measurements are done with high spatial resolution. The application as a medical device and in vivo experiments have to be anticipated by characterization with a measurement setup that simulates natural conditions. Good results are achieved with a pressure chamber which applies a well defined pressure with a soft tubular membrane. It is shown that the proposed catheter design reaches accuracies down to 1mbar and 1cm.

8439-02, Session 1

Dental composite resins: measuring the polymerization shrinkage using optical fiber Bragg grating sensors

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In the search towards aesthetical tooth replacing solutions, dental resin cements play more and more a crucial role. Within the field of adhesive dentistry, the dental cement or composite material is used as filling or restoring material to save a maximum amount of dental tissue. Such a treatment can be applied in case the patient suffers from dentinal caries, a trauma or an irregular tooth morphology. On the other hand, in dental prosthetics the cement is applied as bonding material between the original tooth surface and the restoring material. When setting any composite resin cement, polymerization is needed to transform the original monomer molecules of the resin cement to better-ordered and solid polymers. The more molecules are converted to polymer chains to form rigid structures (the degree of conversion of the polymer), the larger the volumetric shrinkage of a composite resin cement will be. When a cement polymerizes with adhesion to other materials, this shrinkage process will induce stresses in the cement.

A number of devices for determining the volumetric curing contraction and monitoring the polymerization-induced strain have been reported in the dental literature, most of which are based on resistive strain gauges. However, the search for an ideal apparatus for measuring continuous volumetric polymerization shrinkage of resin composite materials still goes on in dentistry. Moreover, the non-biocompatibility of the materials involved in traditional measurement tools and their sizes do not allow for real-time in-situ monitoring of the shrinkage of the dental resin cement, even in oral cavities. This was one of our major driving forces to start investigating optical fiber sensors (OFSs) as an alternative measurement technique. Optical sensors based on fiber Bragg gratings (FBGs) are nowadays the most common optical method for strain monitoring.

In this work, FBG sensors were used as strain sensors and the temperature changes of the samples during the light curing were not compensated as we expect minor temperature changes at the sensing area. FBG sensor fibers are single mode fibers having a 8µm core, 125µm cladding, and 245µm polymer coating diameter (SMF28 Corning). The FB gratings were written in the fiber core over a length of 3 mm. As light source we use an amplified spontaneous emission (ASE) source with a broad wavelength range between 1520 and 1620 nm. Finally the changes in the center wavelength of the Bragg peaks are monitored in reflection using an optical spectrum analyzer (OSA). To control the different devices in the set-up and to perform the data acquisition we use in-house written software based on Labview. All the resin samples were cured in an inox mould having a 20mm×2mm×4mm volume. The 3-mm long grating of the sensing fiber was symmetrically fixed into a 1 cm long stainless steel capillary that was placed into the inox mould and embedded into the resin sample. The capillary was fixed from both ends to protect the FBG from transversal strain, however the fiber was free to move longitudinally i.e. the longitudinal strain sensitivity is not affected. After a prestrain of 1000µ the mould was carefully filled with resin cement to be free of defects, such as small air bubbles. The samples were light cured in the silicone mould for 240 s using a light curing unit having 300-500 mW/cm^2 blue light intensity (410-500 nm). During the curing process the tip of the light curing unit was kept at a 4 mm distance above the cement specimen. During the experiment the Bragg versus time was registered.

The polymerization shrinkage and its induced stress for three different materials were studied: matrix-filled BisGMA-based resins, glass ionomers and organic modified ceramics. At the conference we will discuss the results obtained with Bragg grating based fiber sensors and benchmark the latter with those obtained with a classical dilatometer.

8439-03, Session 1

Macromolecular detection of streptavidin with gold-coated tilted FBG refractometers

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Thanks to a gold coating deposited around a Tilted Fiber Bragg Grating (TFBG), the generation of surface plasmon resonances (SPRs) can occur. TFBG transmission amplitude spectra are characterized by a core-mode resonance and several tens of cladding-mode resonances. When the effective refractive index and the polarization state of the TFBG cladding modes are equal to those of the plasmon wave, there is a transfer of energy to a plasmon. This generation of SPRs impacts the TFBG transmission spectra. For a given linear state of polarization, a minimization of the amplitude of cladding modes is obtained around the SPR wavelength, which is very sensitive to the surrounding refractive index (SRI). As a consequence, the gold-coated TFBG can be deployed for biochemical sensing. We use SPR-TFBG sensors to detect macromolecular interactions based on the affinity streptavidin/biotin.

6° TFBGs were written into hydrogen-loaded single-mode standard fiber using the phase mask technique at 244 nm. 50 nm thick gold coating was deposited by sputtering process. A rotating clamp was used in the chamber to ensure a well uniform gold sheath all around TFBGs. Biotin molecules were then grafted on the gold coating by covalent bond. This process was monitored on the TFBG transmitted spectrum through a red shift of the SPR wavelength. The functionalized TFBGs were used to detect streptavidin dissolved at different concentrations in PBS (phosphate buffer solution). First, the gold-coated TFBG with biotin was immersed in PBS to obtain a reference transmitted spectrum. Then, the sensor was immersed in streptavidin solutions while the SPR signature was continuously tracked. The interaction between the macromolecules impacts instantly the TFBG transmitted spectrum. There is a pronounced wavelength shift of the SPR signature, which is proportional to the streptavidin concentration in the solutions, up to the saturation of biotin. Orthogonally polarized amplitude spectra were recorded by an optical vector analyzer and a linear polarizer. They were compared resonance peak by resonance peak to automate the demodulation process and ensure a real-time operation of the sensing platforms.

8439-04, Session 1

Highly sensitive temperature and strain sensor based on all-fiber 45 degree-TFG Lyot filter

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Lyot filter is a kind of polarization interference filter, which was invented by Bernard Lyot in 1933. It is formed by placing a birefringence medium (BM) between two parallel polarizers whose axes are aligned at 45° with the BM axis. The Lyot filter can be used as comb transmission filter, as it generates continuous wavelength-dependent transmission spectrum. Recently, we have demonstrated a new type of in-fiber polarizers based on fiber gratings with structure tilted at 45°. Such 45° tilted fiber gratings (45°-TFGs) have been UV-inscribed on to standard telecom (ST) and polarization maintaining (PM) fibers and exhibited polarization extinction ratio (PER) as high as 35dB. All-fibert Lyot filters were implemented by concatenating two 45°-TFGs with a PM fiber cavity. Various designs of cavity length have been theoretically and experimentally investigated and we have revealed that the free spectral range (FSR) of the 45°-TFG based Lyot filter is inversely proportional to the PM fiber cavity length. We have further investigated the strain and temperature sensitivity of the 45°-TFG Lyot filter. The all-fiber 45°-TFG Lyot filter with an 18cm long PM fiber cavity was subjected to temperature sensing by heating its middle section of 6cm from 10°C to 50°C. This Lyot filter has shown a remarkably high temperature sensitivity of 0.616nm/°C, which is more than 60 times higher than a normal fiber Bragg grating (FBG) sensor. The 18cm middle section was then subjected to strain variations up to around 550μ and the filter has exhibited a strain sensitivity of 0.025nm/μ, which is 25 times of that of a normal FBG. Such remarkably high sensitivities would make 45°-TFG based Lyot filters as ultra-sensitive sensors to detect very small changes in displacement, strain, temperature and other physical parameters. Alternatively, they may be implemented as tuneable filters with low driving cost and super-fine tuning range.

8439-05, Session 1

Toward the implementation of flexible sensing sheet with fibre Bragg grating sensing elements

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Improved optical sensing sheets based on fibre Bragg grating (FBG) sensing elements embedded in flexible polydimethylsiloxane (PDMS) are proposed. The device can be employed for pressure mapping or tactile applications, in the fields such as robotics and clinical medicine.

Compared to conventional electronic techniques adopted in pressure mapping devices, FBG sensors have specific attributes such as immunity to EMI and harsh environment, absence of sensor driven current and wavelength-encoded signal. Furthermore, FBGs inscribed in highly-birefringent fibres reflect two Bragg peaks, and can use either individual peak shifting or peak separation as the sensing signal. The second working principle shows potential to resolve strain and temperature, based on two parameter techniques. And the feasibility investigation regarding this also inspires this work.

All prototypes were produced with moulding technology. Aluminium moulds with fibre alignment features were fabricated by micro-milling; after fibres were pre-stretched and fixed in the mould, degased PDMS (Sylgard 184) was poured in and cured under room temperature to prevent thermal stress, due to the different coefficients of thermal expansion of silica glass and PDMS.

First prototype of optical sensing sheet contains FBG sensing elements embedded in the middle layer of a complete PDMS sheet, with a thickness of 2 mm. When transverse pressure in the range of 0-250 kPa is applied with a 10mm×10mm steel pin, both peaks shift simultaneously and exhibit a rather linear pressure sensitivity of about 2.6 pm/kPa, while no evident change of peak separation was observed. This is mainly due to the softness of the host material PDMS and no cross-sectional deformation of the embedded fibres arises. Besides, adjacent FBGs multiplexed in the same fibre have inevitable cross-talk, which decreases the spatial resolution and sensing accuracy.

Accordingly, second prototype with modified sheet surface structure was fabricated. Special square pockets were created on the sheet surface to reduce the cross-talk between adjacent FBGs, while other parameters remained the same. Although slightly smaller pressure sensitivity of about 2.1 pm/kPa was registered, using peak shifting as the sensing signal, the cross-talk is significantly suppressed, which is favourable to retrieving pressure mapping during application. This improvement is also validated by finite element analysis.

Third prototype towards the resolving of strain and temperature is designed by introducing hard inserts to realize stress concentration in the cross-section of the fibres. Distinctly asymmetric stress distribution in the cross-section of the fibre results in variation of fibre birefringence, which is the main cause of the change of peak separation. Finite element analysis reveals that by adding two parallel splints to clamp the FBG sensor, there is distinct stress distribution along the two orthogonal axes of the fibre. Nevertheless, challenges remain for precise alignment of the fibre axes and the experimental validation is still under way.

8439-06, Session 1

Fiber Bragg grating for distributed fiber sensor with millimeter spatial resolution

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We have experimentally demonstrated a new architecture to interrogate distributed temperature and/or strain with high efficiency, which makes use of a long fiber Bragg grating (FBG) with a very low reflectivity (overall integrated reflectivity along the entire grating must be less than 10 %). When an optical probe pulse is sent into the fiber Bragg grating, it will be continuously back-reflected while propagating through the whole length of the FBG. In turn, time-resolved spectral profiles of FBG reflection resonance can be measured simply by scanning the central frequency of the probe pulse with an appropriate step. As a result, information of truly distributed temperature and/or strain can be deduced by determining peak frequency of back-scattered light since the central frequency of the FBG reflection resonance has a linear dependence on temperature and/or strain applied to the FBG. This type of distributed sensor has two crucial advantages when compared to any distributed sensing systems based on stimulated light scattering in fibers. First, the proposed system eliminates the need of optical pumping, which is essentially required to create a grating reflector in fibers. Consequently, it renders the sensing system extremely simplified and cost effective. Secondly, the spatial resolution of our sensing system can be significantly improved since the role of the probe pulse is only to read out the grating properties. In this paper, we will present a complete analysis on optical properties of the long FBG and experimental demonstration of distributed temperature sensing to prove the concept of the proposed sensor. A 10 cm-long FBG with a reflectivity of 40% was used as a distributed sensor and an optical pulse with FWHM duration of 50 ps, corresponding to spatial resolution of 5 mm, was launched into the grating to verify a 5 mm-long hot spot.

8439-07, Session 2

Brillouin distributed sensing using localized and stationary dynamic gratings

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In this work, we propose, demonstrate and apply a novel technique for the generation of SBS dynamic gratings that are both localized and stationary. The method relies on the phase modulation of the two pump waves by a common pseudo-random bit sequence (PRBS), with a symbol duration that is much shorter than the acoustic lifetime. This way the acoustic wave can efficiently build up in the medium only at locations where the phase difference between the 2 waves does not temporarily vary, which occurs only at well definite locations as a result of the counterpropagative directions of the interacting waves. Similar to the Brillouin correlation domain analysis (B-OCDA) technique, the method allows for an effective SBS interaction in discrete correlation peaks only. Unlike B-OCDA, however, the separation between neighbouring correlation peaks can be made arbitrarily long, and no modulation of the readout probe wave is necessary. Using the proposed method, we experimentally demonstrate distributed temperature sensing with cm-scale resolution, based on modifications to both the local birefringence and the local Brillouin frequency shift. Like the B-OCDA technique the localization method does not require wideband detection and can generate the grating at any random position along the fibre, with complete flexibility. The results illustrate the potential impact of the proposed technique in measurement of the local Brillouin gain spectrum along an optical fibre with centimetric spatial resolution. The phase-coding method is equally applicable to high-resolution, SBS distributed sensing over standard fibres.

8439-08, Session 2

Fiber optic Brillouin distributed sensing using phase-shift keying modulation techniques

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Fiber optic distributed sensors have attracted interest worldwide over the last two decades for monitoring solutions in, e.g., civil engineering or petrol industry. One of the most popular techniques is Brillouin optical time domain analysis (BOTDA) that enables distributed strain and temperature sensing with meter spatial resolution over 50 km. In this work we demonstrate two new BOTDA sensing systems based on digital (DPSK) and quadrature (QPSK) phase-shift keying modulation techniques with enhanced performances. First we demonstrate Brillouin echoes distributed sensing (BEDS) with centimeter resolution using a single intensity DPSK modulator for the pump pulse. BEDS is a pump-probe technique using π-phase pulses on the pump side. Instead of using one intensity and one phase modulator, the optical π-phase pulse is directly generated at the end of an intensity pulse using DPSK technique. This allows an easy adjustment of the delay between the intensity and phase pulse and improves the optical loss of the pump. Moreover it lowers the cost and simplifies the setup. Results comparing the standard BEDS system with the new DPSK-BEDS system are shown with 5cm spatial resolution and a strain measurement is performed. The second technique uses a QPSK modulator as a single sideband (SSB) modulator for the probe wave. The advantage of QPSK modulator compared to dual-drive modulator lies on the high performance of carrier suppression of 55 dB as well as side-mode suppression of 40 dB at 1535 nm. As a single side band is used as the probe, no additional filter is needed before the photo detector. Although the QPSK modulator has a high optical insertion loss, the distributed measurement signal has a higher contrast than that using a conventional intensity modulator and an fiber Bragg grating (FBG). By use of the QPSK modulator the performance of BOTDA using either Stokes or Anti-Stokes component is shown and discussed.

8439-09, Session 2

High-resolution Raman-assisted Brillouin sensor based on differential pulsewidth pair technique

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A high resolution technique, so-called Differential Pulse-width Pair (DPP) [1], is employed in order to provide 1 meter resolution to a 100 km-range Raman-assisted Brillouin Optical Time Domain Analysis (BOTDA) distributed temperature sensor. Previous works on such a long distance sensor have always achieved resolutions of 2 meters or more [2]. Higher resolutions employing the conventional configuration yield undesirably large uncertainties due to the well-known resolution-uncertainty trade-offs, as well as self-phase modulation issues.

The resolution of a BOTDA is conventionally determined by the width of the pulses employed to generate the pump signal (e.g. 1 meter resolution is obtained with 10 ns pulses). In addition, the width of the Brillouin gain and therefore the uncertainty in the determination of the Brillouin shift is given by the convolution of the pump spectrum (broader for shorter pulses) and the natural Brillouin gain in the fiber. A natural limit in resolution is given when the pump pulses are in the order of twice the phonon lifetime, which is roughly equivalent to 10 ns in typical fibers.

To avoid this issue, differential techniques allow increasing the resolution of BOTDA fiber sensors without broadening the gain spectrum. In this work, we employ the DPP technique, which bases its working principle in the subtraction between gain traces obtained with slightly different pulse widths. The resolution in this technique is given by the differential width between the pulses while the broadening in the gain remains bounded since the pulses used are always much longer than the phonon lifetime. When the two gain signals are subtracted, the remaining gain is theoretically caused by the pulse-width difference.

In this work, 50 ns and 40 ns pulses were employed to sense a 1 meter hot-spot in the fiber. At each measurement (50 and 40 ns), the gain at the hot spot is spread over 5 or 4 meters, respectively. When both traces are subtracted, the gain of the 1 meter hot region remains clearly visible and the temperature difference is well discriminated. The measurement of the hot spot is developed in the position of worst contrast of the fiber, showing that all the positions can be well determined using this technique.

[1]- Differential pulse-width pair BOTDA for high spatial resolution sensing. W. Li, X. Bao, L. Chen, Optics Express, Vol. 16, Issue 26, pp. 21616-21625 (2008)

[2]- Hot spot detection over 100 km with 2 meter resolution in a Raman-assisted Brillouin distributed sensor. X. Angulo-Vinuesa, S. Martin-Lopez, J. Nuño, P. Corredera, J.D. Ania-Castañon, L. Thévenaz, M. Gonzalez-Herraez, Proceedings SPIE, 7753 pp. 775309

8439-10, Session 2

Optical time-domain reflectometer-based multiplexed sensing scheme for environmental sensing

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In our study remote environmental sensing is presented using a standard optical time domain reflectometer (OTDR).

The measurement of environmental parameters using optical sensors

is an expanding area of research with growing importance. Fiber optic sensors are an interesting solution for that due to their high sensitivity, small size, and capability for on-site, real-time, remote, and distributed sensing capabilities.

Our multiplexing sensing scheme approach uses, transmissive filters, long period gratings (LPGs) being interrogated by the OTDR return pulses that are plotted as a function of the fiber length. The loss induced at the resonance wavelengths varies with the environment refractive index temperature or other physical parameters changes.

Experimental results show that the insertion of an erbium amplifier improves the the measurement resolution. The analysis of this remote multiplexed sensing scheme behaviour allows us to perform simple and low cost real time measurement of refractive index over long distances.

8439-11, Session 2

Distributed optical fibre temperature measurements in a low dose-rate radiation environment based on Rayleigh backscattering

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On-line monitoring of environmental conditions in nuclear facilities is becoming a more and more important problem. Standard electronic sensors are not the ideal solution due to their sensitivity to radiation and difficulties in installation of multiple sensors. In contrast, radiation-hard optical fibres can sustain very high radiation doses and also naturally offer multi-point or distributed monitoring of external perturbations, which facilitates the detection of hotspots. Multiple local electro-mechanical sensors can be replaced by just one measuring fibre.

At present, there are over four hundred operational nuclear power plants (NPPs) in the world. Operating experience has shown that ineffective control of the ageing degradation of major NPP components can threaten plant safety and also plant life. Among these elements, cables are vital components of I&C systems in NPPs. To ensure their safe operation and predict remaining life, environmental monitoring is necessary. In particular, temperature and radiation dose are considered to be the two most important parameters.

The aim of this paper is to assess experimentally the feasibility of optical fibre temperature measurements in a low radiation dose-rate environment, based on Rayleigh backscattering using a commercially available reflectometer. Four different fibres were installed in the Sub-Pile Room of the BR2 Material testing nuclear reactor in Mol, Belgium. This place is man-accessible during the reactor shut-down, allowing easy fiber installation. When the reactor operates, the dose-rates in the room are in a range of 0.5 - 5 Gy/h with temperatures of 40 - 60 °C, depending on the location. Such a surrounding is not much different to some “hot” environments in NPPs, where I&C cables are located.

In the presentation we will describe the optical fiber installation in the Sub-Pile Room, temperature measurements based on Optical Frequency Domain Reflectometry and their comparison with measurements performed with standard resistive temperature sensors. Suggestions on the selection of fibres suitable for such an environment will also be given.

8439-12, Session 2

Development of a Jones vector-based model for the measurement of a plasma current in a thermonuclear fusion reactor with a POTDR setup

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Fiber optical current sensor (FOCS) is a promising alternative to inductive sensors for the measurement of the plasma current in future thermonuclear fusion reactors. Standard FOCS relies on the measurement of the state of polarisation (SOP) of light at the output of an optical fiber surrounding a current. Because of the Faraday effect, magnetic field induced by electrical current rotates the SOP of light travelling into the fiber. According to the Ampere theorem this rotation is proportional to the surrounded current. In future tokamaks like ITER and DEMO, the plasma current will be sufficiently high to generate a rotation of the SOP higher than 2π radians. These conditions will lead to uncertainties on the determination of the plasma current. In this paper we propose a solution with a Polarisation Optical Time Domain Reflectometer (POTDR) setup for plasma current measurement. This measurement is based on the assessment of the SOP rotation of the Rayleigh backskattered OTDR signal. Thanks to the presence of an input polarizer, SOP variations are converted into power fluctuations that contain information about the distribution of the magnetic field and therefore about the plasma current. We use the Jones formalism to develop a model describing the modification of the SOP of light and the evolution of the POTDR trace. Theoretical results are compared with experimental POTDR traces measured on the thermonuclear fusion reactor Tore Supra situated at CEA Cadarache in France.

8439-57, Poster Session

Challenges and mitigation methods for diode laser absorption spectroscopy-based sensor implementation for power plant diagnostics

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With the advent of renewable energy sources, the fossil fuel based energy products are forced to break new grounds on efficiency, performance, reliability, and operational flexibility.. Tunable diode laser absorption spectroscopy based (TDLAS) techniques/ sensors have enabled rapid developments in the field of monitoring and diagnostics for gas and steam turbines. These sensors are mostly based on line-of-sight absorption spectroscopy measurements and can help in sensing a variety of important machine parameters like, emissions, operating temperatures, and moisture fraction. In the near future, diode laser spectroscopy and related technologies are extremely promising and show immense potential towards delivering fast, accurate, and in-situ monitoring and diagnostic capabilities to the power generation industry.

Though TDLAS based sensors offer a promising technology for advanced control and optimization, they are limited in application by harsh environment conditions like high pressure and temperature, vibrations, scattering and unpredictable scattering losses. There are many reports in the literature for the correction of above parameters using 2f/1f method. Unfortunately, 2f/1f is not enough to address the field scenario. A reliable spectroscopic measurement in such environment requires careful absorption line selection, scattering correction, alignment correction and accounting for the effects of pressure and temperature on the absorption light-strength.

In this article, we have described challenges of the laser based sensor field deployment in power plants. The extreme temperature and vibration of power generation equipment cause misalignments of the TDLAS system leading to erroneous measurements of the exhaust gases. We have designed active servo auto alignment system to keep the line of sight intact and appropriate algorithm to compensate for window clogging and scattering correction. During the cold start process, the vibration frequencies are of the order of 20-120Hz (depending on the system design) and thermal transients 12ºC to 200ºC. So it needs active and fast response (~5ms) to compensate the vibrational instability. The auto-alignment system has a response time of 3 minutes which was sufficient to mitigate any mis-alignments due to thermal transients. Using the auto-alignment and scattering correction method, we were able to detect ammonia emissions as low as 0.1ppm.

8439-58, Poster Session

Optoectronic phase noise measurement system with wideband analysis

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It is possible to determine the spectral density of phase noise for oscillators compared to another one with the same frequency if noise is expected to be better than a synthesizer. That's why there is a need to develop methods based on the use of two delay lines and cross correlation to be able to characterize an oscillator without referring to another one with the same delivered frequency. We achieved a low phase noise optoelectronic measurement system based on optic delay line and cross-correlation method to characterize microwave single oscillators in X-band. A 2 km optical fiber provide a to = 10 µs delay. It makes possible the phase noise characterization up to 10^5 Hz from the carrier. This limit is due to the periodicity of the delay-line phase. It produces a series of noise peaks at frequency multiples of 1/to. This peaks have extremely narrow bandwidth, in the hertz range, but in simulations and experiments they seem significantly wider because of the insufficient resolution. The peak height follows the law £(f) proportional to 1/f^4 corresponding to –40 dB/decade. Noise floor of the developed instrument is respectively –90 and –170 dBc/Hz at 10^1 and 10^4 Hz from the 10 GHz carrier. It can be noticed that noise of the best commercial synthesizers are usually in respectively in the range of –70 and –120 dBc/Hz at 10^1 and 10^4 Hz. It justify our development. To increase the performances of the developed optoelectronic phase noise system, we introduce another pair of optic delay line based on a 100 m short fiber in addition of the 2 km fiber. It corresponds respectively to a 500 ns delay. So Fourier frequency analysis can be extended from 10^5 to 2.10^6 Hz. However sensitivity of the system is worse for lowest Fourier frequency with a shorter delay. We must then keep the long delay line for determining phase noise closer from the carrier. To determine the phase noise on a larger band, a switch electrically controlled is placed on each arm of the system, the signal propagates through the photo detector across an optical coupler. In this work we present these last developments.

8439-59, Poster Session

The optic-electronic autocollimation sensor for measurement of the three-axis angular deformation of industry objects

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The monitoring of the industrial, science and power- plants constructions calls for the high-precision measurements of angular tilts and deformation with an error within 1 arc seconds in a range to several tens of arc minutes.

Optic-electronics autocollimation sensors for non-contact measurements are used effectively. The sensor consists the autocollimator on a rigid base outside the controlled object and the optical reflector element on the controlled object.

The tilt of the object is determined by three angular coordinates. They are pitch, yaw and roll.

The ordinary autocollimation sensor uses the plane mirror as reflector element. This sensor measures only two angle coordinates - yaw and pitch for rather small range. The three-axis autocollimation sensor for measure the yaw, pitch and roll with necessary measuring range and work distance uses the cube- corner optical reflector element with non-plane facets.

The structure form of the optical reflector element for three-axis autocollimation sensor is the glass prism tetrahedron. Two facets are the plane and third facet is the cone or cylinder segment.

The collimated beam reflects from three facets of the optical reflector element and returns to the objective of autocollimator.

The reflector with the cone segment transforms the collimated beam into the beam with ribbon structure.

As result the reflected beam forms the image as the four ellipse arcs into the matrix photo receiver at focal plane of the autocollimator objective.

After objects rotation the parameters of ellipse image are changed. The size of axle ellipse varies proportion to pitch angle, the image rotates relative to the centre as the roll angle and the two ellipse arcs rotate relative to the another arcs as the yaw angle.

These parameters of the ellipse are calculated after image processing and the pitch, yaw and roll rotations of the object are determined.

The great attention during the research is paid to the experimental approval of the theoretical results. The parameters of the experimental autocollimator are: infrared emission diode AL107B by power 15 mWt as sources of radiation; the objective by the focal length 450 mm, the CMOS matrix receiver by type OV05620 Color CMOS QSXGA with 2592*1944 pixels and one pixel size (2.2*2.2) micrometers produced Omni Vision as image analyzer. The experimental measuring error of the yaw and pitch angle is 1.5 arc. seconds at the angular region 20 arc. minutes and the measuring error of the roll angle is 5 arc. seconds at the angular region 1 degree.

The experimental research of the optic-electronic system for the measure deformations of the elevation axle of the large size radiotelescope confirms the advantage of the three-axis autocollimation sensor with tetrahedron reflector element.

8439-60, Poster Session

Design and implementation of IR microspectrometers based on linear-variable optical filters

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Low-cost single-chip spectrometers have huge potential in systems for biomolecule identification and chemical analysis by optical absorption, fluorescence and emission line characterization. Such microspectrometers offer significant advantages over existing instruments, including size reduction, small sample size, low cost, fast data-acquisition and high reliability. Many interesting gases (e.g. CO, CO_2, N_2O, C_xH_y) have absorption spectra in the 1000 nm - 5000 nm spectral range. Moreover, many liquids (e.g. methanol, ethanol, water, oil) can be identified using their IR spectral absorption signature. A Linear Variable Optical Filter (LVOF) is based on a tapered cavity on top of a linear array of photodetectors and enables the transfer of the optical spectrum into a lateral light intensity. The same concept of the system can be designed and realized for wavelengths from UV to IR (300 nm - 5000 nm). The difference is in the choice of the dielectric materials and the layer thickness. This paper presents the design, fabrication and characterization of Infra-Red (IR) Linear Variable Optical Filter (LVOF)-based micro-spectrometers. Two LVOF microspectrometer designs have been realized: one for operating in the 1400 nm to 2500 nm wavelength range and another between 3000 nm and 5000 nm. The IR LVOF has been fabricated in an IC-Compatible process using resist reflow. The LVOF provides the possibility to have a small size, robust and high-resolution micro-spectrometer in the IR on a detector

chip. Such IR microspectrometers can be fabricated at low-cost in high volume production and have huge potential in applications such as liquid identification (e.g. water in alcohol, water in oil) and gas sensing.

The spectral resolution of a Fabry-Perot interferometer is determined by surface flatness, parallelism between the two mirror surfaces and mirror reflectivity. The possibility to have high number of spectral channels in an LVOF spectrometer theoretically makes it possible to have high spectral resolution in the IR spectrum range using signal processing techniques. For a Fabry-Perot type of LVOF, the thickness variation of the cavity layer has to be in order of quarter of the wavelength and very well controlled, which makes fabrication of miniature LVOFs a technological challenge.

SiO_2 and Si have been used as high-n and low-n materials. The transmission of the Fabry-Perot is simulated with TFCalc®. The thickness of the tapered cavity layer changes linearly from 1000 nm to 1800 nm. Similarly, the designed thicknesses for the multilayered LVOF which is intended for use in the 3000-5500 nm wavelength range are given. The thickness of the tapered cavity layer changes linearly from 2300 nm to 4000 nm.

Two types of LVOF have been designed, fabricated and validated for use between the near and mid infrared wavelength range. The spectral peaks have been measured with the conventional spectrometer. It has been shown the potential for a low cost solution for the microspectrometer applications.

8439-61, Poster Session

Noise analysis of a CCD-based ultraviolet spectrometry system

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CCD optical spectrometers are used in a wide range of fields, such as medicine, process control and scientific research. They are in common use in the measurement of UV-absorbing gases of environmental concern such as SO_2, NO_2 and the BTEX compounds (benzene, toluene, ethylbenzene and xylene), especially as their small size and relatively low power can enable the development of portable equipment. A spectroscopic measurement system consists of a broadband light source, light delivery / sample chamber and spectrometer. Typical configurations include short path, pumped gas sample cells and long, open path measurements used in air quality or emissions monitoring, the latter often being used to measure the differential spectrum in a technique known as differential optical absorption spectroscopy (DOAS). In this paper, we characterise the noise behaviour of a spectrometer system that takes advantage of new developments in CCD and UV LED technology, and we make comparisons with a conventional light source (a deuterium lamp).

The noise behaviour was first assessed for a CCD spectrometer (Avaspec-3648-USB2-SPU2) during standard operation, involving no external controls or noise limiting post-processing. A range of integration times was investigated with the light sources listed above. Both rapid fluctuations in measured intensity (< minutes) and longer term drift (up to several hours) have been considered. Wavelength stability was investigated within the resolution limits of the spectrometer.

We have also investigated a post processing scheme, in which signal averaging uses an optimised combination of CCD integration and computer based averaging over multiple measurements. The results demonstrate a significant reduction in measured fluctuation noise. An attempt is made to identify and quantify different noise phenomena, noise levels under optimum conditions are characterised and some recommendations for operation are made. The results are related to the requirements of detection of gases such as NO_2 and SO_2 at the ppm level.

8439-62, Poster Session

Silicon-on-insulator (SOI) nanobeam optical cavities for refractive index-based sensing

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1-D photonic wire microcavities also known as nanobeam cavities are one of the emerging configurations for refractive index based optical sensors. Here, we present the design modelling and fabrication of Silicon-On-Insulator (SOI) nanobeam cavities that are immersed in a microfluidic system. The ability to detect small refractive index changes in analytes is important since these changes of index can be directly correlated to the presence of small amounts of different chemicals of interest within analytes. We present a simple optical technique of detection based on nanobeams that gives good sensitivity for various chemicals. The sensitivity of such optical sensor depends on the sharpness of the resonance wavelength (Q-factor), and the achievable resonance wavelength shift. As the mode oscillates between the two mirrors, the mode overlaps with the analytes which results in a potentially large wavelength shifts. In order to optimize and fine-tune the nanobeams, we have used tapering holes inside the cavity. The sensitivity requirements are obtained by confining the light in cavity mode and overlapping it with the analytes. When the light is strongly confined in the cavity mode, the sensitivity, $S = \Delta \ /\Delta n$ has a value greater than 200 nm/RIU (RIU = refractive index unit). We have modelled and optimized a suspended nanobeam cavity working in a water-based (n = 1.333) environment and achieved a Q-factor of more than 20 000. With this simple approach, we show that very small changes in refractive index can be detected and can be used for biological sensing.

8439-63, Poster Session

Characterization of MRI-compatible PET detector modules by optical excitation of the scintillator material

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In the field of biomedical imaging there is a strong interest in combining modalities of PET (Positron Emission Tomography) and MRI (Magnetic Resonance Imaging). An MRI-compatible PET detector module has to be insensitive of the magnetic field, that is why it needs to incorporate avalanche photodiodes (APD) or silicon photomultipliers (SiPM). In case of the conventional photomultiplier tube (PMT) based modules the characterization is usually carried out by a collimated nuclear radiation. We propose a new, purely optical characterization method for these devices where no nuclear source is needed. Our method is based on the fact that one of the most frequently used scintillation material, lutetium-yttrium oxyorthosilicate (LYSO) has very similar fluorescent and scintillation spectra. In our method we use LED sources for both direct illumination of the silicon sensors and UV excitation of the scintillator material. Using an LED with a peak emission close to that of the LYSO we can measure the linearity and homogeneity of each pixel as well as optical cross-talk between the pixels. In the same experimental setup we can also emulate the pulse response of the detector module (i.e. light-spread over the sensor array from a point source in the scintillator material) by focusing UV light into the detector geometry. This latter investigation is important in case of the newly investigated continuous scintillator approach. State of the art commercial PET detectors utilize scintillator crystal pin matrixes to collect more light from a scintillation, but at the same time loosing depth information along the pin axis. The pulse response of these blocks is independent of the depth of the scintillation, so they can be characterized by collimated gamma source. The same cannot be used in case of the continuous detector approach. We present the verification of the experimental setup by measuring the emission spectra of the light sources and measuring the light distribution of the illuminating optics. We also analyze the benefits and drawbacks of this method compared to the nuclear measurements. The viability of the idea is proven through the characterization of a SiPM array and a block detector module based on it.

8439-64, Poster Session

Polarization dependence of the strain sensitivity of fibre Bragg gratings inscribed in highly birefringent optical fibres

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Fibre Bragg gratings (FBG) inscribed in single mode optical fibres are currently employed as strain and temperature sensors in a huge variety of applications [1]. In order to expand the spectrum of applications for FBG-sensors, increasing the accuracy of FBG-based measurements is often required. Some limiting factors of the measurement accuracy are non-reproducible polarization effects, which are due to birefringence in the optical fibre at the location of the FBG which is induced by both, the FBG inscription process and the attaching mechanism (i. e. embedding or gluing) of the sensor fibre to the structure to be measured.

In order to avoid an unknown quantity and orientation of the fibre's birefringence and an undefined state of polarization of the interrogating light, we inscribed FBGs into highly birefingent optical fibres. These "hibi-FBGs" were attached to a specimen with defined orientations of the fibre's slow and fast axes with regard the specimen's surface. The reflected spectra of the FBGs were observed for each polarization mode separately. The strain sensitivity of a fibre Bragg grating (FBG) is defined as the relative shift of the Bragg wavelength per longitudinal strain. The strain sensitivities were determined for each polarization mode and for different fibre orientations using a strain calibration facility as described in [2]. According to the guideline for optical strain gages, the uncertainties of the calibration procedure should be less than 0.5% [3]. It was found that in all experiments the strain sensitivity for the slow axis was significantly higher (about 0.8%) than for the fast axis. The strain sensitivity was also dependent on the orientation of the fibre's birefringent axes with regard to the surface of the specimen.

These results are important for improving the accuracy of FBG-based strain sensing and for assessing the uncertainty of FBG-based strain measurements in standard monomode fibres.

1. Kashyap, R., [Fiber Bragg Gratings], Academic Press, San Diego & London, (2010)

2. Roths, J., Wilfert, A., Kratzer, P., Jülich, F., Kuttler, R., "Strain calibration of optical FBG-based strain sensors" Proc. SPIE 7653, 76530F (2010)

3. VDI/VDE 2660: Optischer Dehnungssensor basierend auf Faser-Bragg-Gitter. Düsseldorf, (2009), in German

8439-65, Poster Session

Field testing of a low-cost self-referenced all-fibre polarimetric current sensor for the monitoring of current in the high-speed railway catenary

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In this paper we present the field testing results of a low-cost all-fibre polarimetric current sensor for the monitoring of current in the European high-speed railway network. The sensor fulfils the requirements of robustness, sensitivity, accuracy and cost required for the monitoring of catenary current in changeover sections. Changeover sections are non-fed sections of the catenary that are placed between sections fed with different phases and that introduce discontinuities in the current collection done by the train. Since the train passes at high-speed between the two sections, the electric arc formation may lead to significant damage of the infrastructure. To avoid this situation, it is essential to ensure the switch-off of the current collection before arriving and switch-on again when the changeover section is passed. An adequate protection system that monitors the current in the catenary before the changeover section allows to trigger the necessary protection mechanisms in the infrastructure. Efficient, robust and lightweight electrical current sensors are therefore essential for this security system.

The sensor proposed here uses the Faraday magneto-optic Effect with a well-known polarimetric interrogation method [1]. The optical configuration is extremely simplified through the use of few cost-effective, all-fibre devices with a simplified alignment. It allows high sensitivity for low current values, demonstrating a resolution below the ampere level with a dynamic range up to 500 A.

The setup is electronically self-referenced to reduce the effect of small misalignments in the polarization, power variations in the optical source, temperature changes, birefringence effect and bending-induced attenuation in the lead fibre. A set of temperature tests in a climatic chamber were also performed in a range of temperature between -20 up to 80ºC, to assess the robustness of the device to operating temperature variations. The field tests include tests during commercial operations and special tests simulating fault conditions.

References

[1] D. Alasia, L. Thévenaz, "A novell all-fibre configuration for a flexible polarimetric current sensor", Meas. Sci. Techn. 15, 2004.

8439-66, Poster Session

Precise fiber optic sensors with pulse modulation of intensity

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Low metrological property of analogue fiber-optic sensors (FOS) leads to necessary refusal from analog principles and to transition to digital ones. Processing the parameters of non-analog signals by digital means assumes the realization of pulse modulation of optical flux in FOS by means of sampling its timely or spatial parameters. Thus we can enter to the optical flux additional non-optical parameters, which could be the recipients of information. At that all advantages of properly FOS remain because optical flux remains an information carrier, as earlier. Here the problem of the precision of measurement is not linked with the measurement of low intensity optical flux; the problem moves from the domain of optical measurements to other non-optical area, where it is resolved properly.

We could realize this approach either by means of creation of special non-analog FOS or by means of using ordinary analog FOS in extrinsic non-analog modes. Signal processing for this FOSs can be performed by the counter, what can guarantee high precision of measurement.

Possibility of computer aided processing of the FOS signal eliminates the intrinsic error and allows eliminating the influence of errors of production and adjustment. It allows to put all intellectual burden during measurements on the unit of signal processing and to diminish the level of requirements to the FOSs under condition of high level requirements to the efficiency of measurements. In this case FOS could be simpler and less costly in production and operation.

Consideration stated here illustrates the possibility of construction of precise three-coordinate digital accelerometer for the measurement of ultra-small linear accelerations, based on the FOS with time-pulse modulation of optical flux intensity.

8439-67, Poster Session

Optical comparison of detector arrays from modulation transfer function measurements with laser speckle patterns

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CCD and CMOS detector matrices offer excellent features in imaging systems. For examining the suitability of one or the other technology according to the specific application, the complete characterization of the different detector types becomes necessary. A system is optically characterized by the modulation transfer function (MTF), which represents the response in spatial frequency of this system. One of the methods to measure the MTF is based on using a laser speckle pattern as the object.

In this work, we have comparatively studied the results provided by the speckle method to determine the MTF for detectors of two types: CCD and CMOS. For speckle-pattern generation, we used an integrating sphere and a He-Ne laser source (λ = 632.8 nm). The laser radiation was aimed at the entrance port of the integrating sphere and the speckle pattern was generated at the exit port, where an aperture was situated. The aperture determined the spatial-frequency content of the pattern registered in the detector.

We studied the precision in determining the MTF of the CCD using two different apertures: a single-slit and a double-slit. For the single-slit aperture, we propose a new procedure of fitting the experimental data which resolves the drawbacks of the conventional procedure. Since our results show that the single-slit offers lower uncertainty and better reproducibility, we have chosen this aperture for the study with the CMOS detector. The differences found between the MTF values of the CCD and the CMOS detectors are significant for the spatial frequencies higher than 50 cycles/mm, which is half of the interval studied with both arrays. For these spatial frequencies, our results demonstrate that the CCD detector presented MTF values higher than those of the CMOS array. Furthermore, the differences between the MTF curves corresponding to both detectors intensify as the spatial frequency augments.

8439-68, Poster Session

Carrier removal method based on the principle of shearing

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In the method of holographic interferometry and three dimensional profilometry of optic projection grating, the reconstruction of real phase will be affected by the carrier frequency, so removing carrier is a necessary step to obtain the accurate real phase. A novel method is proposed by introducing the shearing principle to the calculation of carrier removal. Firstly, the distribution of phase gradient is obtained by shearing the optical field. Then, the mean value is subtracted from the obtained phase gradient to achieve carrier removal. That is, the proposed method is finished before phase unwrapping. The simulation calculation and experiment results show that this method is benefit to reduce the difficulty of phase unwrapping, to remove the carrier frequency effectively, and to make the reconstructed phase more closer to the measured true value.

8439-69, Poster Session

Optical and structural properties of sol-gel immobilized laccase: a first step for its use in optical biosensing

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Laccases are cuproproteins belonging to the group of oxidoreductases and they are able to catalyze the oxidation of various aromatic compounds (particularly phenols) with the concomitant reduction of oxygen to water. They are characterized by low substrate specificity and have a catalytic competence which widely varies depending on the source. Additionally, laccases have also very peculiar optical properties due to their copper active sites which participate to the reduction processes. All these characteristics make laccases very flexible biotic element for biotechnological applications. During the years, a number of studies have been devoted at exploiting catalytic properties of laccases and very few at profiting of its optical properties. A preliminary study by absorption, fluorescence, FT-IR and Raman spectroscopies of commercial laccases from various sources has evidenced their potential usefulness for optical biosensing of phenol compounds as catechol. Moreover the sol-gel process offers a convenient and versatile method for preparing optically transparent matrices at room temperature that can represent a very convenient support for laccase immobilization. Also for immobilised enzymes the above-mentioned techniques have allowed a detailed characterization of their optical and structural properties that confirmed the potentials of laccases for producing optical biosensors and represented a fundamental step in the designing of an optimised optical biosensing scheme.

8439-70, Poster Session

Low-power proximity electronics for dust analyzers based on light scattering

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MicroMED is a dust analyzer derived from the MEDUSA Experiment, proposed for the ExoMars ESA mission. The MEDUSA B/B reached a Technology Readiness Level (TRL) of 5.3 after the Preliminary Design Review (PDR) held in 2009. Due to increasing costs and the lack of funds, the ExoMars mission was reviewed and split in two different missions scheduled respectively in 2016 and 2018. The knowhow related to the experience of MEDUSA allowed the Cosmic Physics and Planetology Group to develop a new instrument, MicroMED, based on the same concept of MEDUSA, i.e. the analysis of the light scattered from particles, but requiring much less resources in terms of mass and power consumption to be compliant with the requirements of the future missions.

In MicroMED, a pump generates a flux of gas and dust, which flows in the instrument through the inlet. The dust particles, after being captured by a sampling head, reach the sampling volume of the Optical System (OS). At the sampling volume, they are illuminated by a collimated IR laser beam, whose direction is orthogonal to the flow direction. The light scattered by the crossing particles is collected by a mirror reflecting the light toward a photodiode placed in front of it. A light trap is placed in front of the laser source in order to minimize the undesired stray light inside the instrument. The PE is aimed to amplify the photodiode output current to obtain an analog voltage signal with the requested dynamics. The data acquisition and the discrimination of relevant information from the background noise are performed by the Main Electronics (ME), separated from the instrument. The measured intensity of the scattered light is a function of the grain size, accordingly to the Mie's theory. The MicroMED measurement range, in terms of particles radius, is from 0.2 to about 15 µm.

To obtain dramatic reduction of the power consumption of the OS PE, with respect to the versions previously implemented for MEDUSA and, even before, for the OS of the GIADA Experiment on-board the ROSETTA ESA mission, two different approaches were followed. The first approach consisted in the optimization of the PE based on a Linear Amplifier, already used for the PE of the two mentioned experiments. The solution based on the linear amplifier exploits as much as possible the heritage of GIADA and MEDUSA experiences and this is the reason why this solution was considered the less risky at the beginning of the development activities.

To implement an optimized solution, a second approach based on the Logarithmic (LOG) Amplifier was also explored, because more promising. In fact it needs only one output line to cover the entire requested dynamics (almost seven decades, as obtained in the previous two MEDUSA B/Bs), instead of two lines, as requested for the linear amplifier. This feature saves both power consumption and mass, because it needs less electronic components and the I/F with the ME (and the related cabling) is simplified.

The LOG Amplifier was never implemented before in OAC and it exhibits the well known problems of thermal stabilization. Consequently, the Linear Amplifier PE was developed before, in order to make available a backup solution to recover from any criticality related to the LOG amplifier development.

In this paper the description of the three kinds of developed PEs is reported: PE based on Linear Amplifier; PE based on Custom LOG Amplifier; PE based on Commercial Off-The-Shelf (COTS) LOG Amplifier.

The results of the functional and performance tests are also briefly summarized. The performance of the boards were verified by feeding their input with a known signal simulating the detector output. In order to test the boards without an optical detector connected to them, the detector current signal was simulated by a Function Generator (mod. HP33120A by Agilent) connected to the boards input. The Function Generator supplied a square wave at different amplitudes and frequencies, to test the PE dynamics at the maximum frequency that the PE amplifier can process without signal distortion. To acquire the overall response of the two LOG Amplifiers, the sawtooth function was also used. The amplifier output signals were acquired by a Digital Oscilloscope (mod. TDS2024B by Tektronix). The tested boards were powered with a PL330QMT power supply by TTi.

NOTE: design information, test results and related diagrams are non reported for brevity

Three electronic boards were designed and manufactured to implement a low power PE for MicroMED. Different approaches were followed, based on a linear amplifier exploiting the heritage of two MEDUSA B/Bs, and two logarithmic amplifiers, one full custom and one based on a COTS component.

The low power Linear Amplifier performs 180 mW of power consumption, about one fifth of the power consumption of the MEDUSA PE. The bandwidth is narrower of the one of the MEDUSA PE, i.e. 25-35 kHz, in any case sufficient to fulfill the MicroMED requirements. This linear amplifier has to be considered as a backup solution with respect to the LOG amplifiers, not developed before for GIADA and MEDUSA Experiments.

The LOG amplifier has been implemented in two versions: one custom and the other based on a COTS integrated circuit. The former gave poor performance in terms of bandwidth at low input current, not compliant with the MicroMED requirement. The latter, based on the COTS AD8304 monolithic LOG amplifier by Analog Devices, showed sharp logarithmic response in the measurement range from 0.1µA to 1mA. Also the noise immunity, power consumption and bandwidth are at levels unattainable by electronic circuits based on standard OpAmps and discrete transistors. The measured power consumption at +5/-1Vdc is only 32mW.

The bandwidth at 0.1 µA peak input current is equal to 30 kHz that is a good figure with respect to the one of the LOG amplifiers based on standard electronic components. The bandwidth at 10 nA peak input current resulted equal to 24 kHz.

For the promising performance of the last solution, the following upcoming activities are planned:

- Performance tests of the COTS LOG Amplifier integrated in the OS at the whole temperature range envisaged for the experiment;
- Integration of the silicon die of the AD8304 in a ceramic package and qualification process related to the actual space environmental conditions, above all the ones concerning radiation;
- Implementation of a miniaturized version of the test board by using Surface Mount Technology (SMT) passive components, instead of the traditional through-hole components to allow drastic dimension and mass reduction.

8439-71, Poster Session

The experimental characterization of the absorption and scatter properties of photopolymers

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In this paper we studied the photosensitivity and scatter properties of several types of photopolymers that are used in different types of applications such as 3D printing processes, rapid prototyping with stereo-lithography, holographic data storage, dental surgery and the flexographic printing industry. For all these applications, in order to predict the behavior of the photopolymer under certain illumination conditions, a model is needed describing the 3D interaction between the incident light and the material. This model should take into account both the optical and chemical aspects involved. For the optical part the absorption and scatter properties of the material should be included in the model.

In our work we applied different measurement methodologies to experimentally characterize both the absorption and scatter properties of different photopolymer materials. In a first part we measured the absorption spectra of different non-cured photopolymers in the range between 350 and 1600 nm. From these spectra we calculated the absorbance coefficients. After this, we repeated this procedure for the cured material which we obtained by illuminating the photopolymers with a laser source. We investigated the absorption properties for different illumination times in the range between 0 and 2000 ms. From these measurements we could calculate for the different materials the difference in absorbance between the cured and the non-cured material. Depending on the material the absorbance of the non-cured material was a factor 20 to 60 higher compared to the absorbance of the cured material. These results were used as input for the optical model.

In a next step we measured the BTDF for the different materials and calculated the scatter angle at $1/e^2$. As a result we obtained scatter angles between 2 and 6°. In a last step we verified and confirmed these differences in scatter behavior by measuring the MTF of a real imaging system that included the photopolymer.

8439-72, Poster Session

The study of vegetation indices for the monitoring of differences in chlorophyll and carotenoid composition in green vegetables

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In this paper we studied the reflectance spectra of different green vegetables. The main objective was to identify the wavelength(s)(areas) that are the most sensitive to variations in pigment composition. With this we try to meet the ever growing demand from society to classify food products on their quality which is related to the state of ripening and degradation. Different bio-chemical reactions take place during these processes with the most important ones the conversion of chlorophyll a molecules into chlorophyll b molecules and in a later phase the breaking-off of the chlorophyll molecules and the accumulation of carotenoid molecules. In our research we worked with two test-cases simulating these processes. In a first test-case the group of investigated samples consisted of a group of seven different green vegetables. Because these products have a different chlorophyll a to chlorophyll b ratio, the spectral variations we observe between these groups will also be seen when a product starts to senescence. Following a similar consideration we studied in a second test-case the reflectance spectra of one particular green vegetable in different stages of maturity. These results give us information about the occurring spectral variations when the chlorophyll molecules are broken off and the carotenoids starts to get the upper hand. For each product type we measured the reflectance spectra between 400 and 800 nm for 30 samples. After this we applied a principal component analysis and studied the principal spectra allowing us to identify those regions that are most sensitive to pigment variations. Finally, we calculated for each product type several vegetation indices that are described in literature and that are applied to monitor plant leaves during their growth. The main conclusion of our research was that those vegetation indices are also very suitable to monitor pigment variations in vegetables and fruits and as such can be used to monitor differences in quality.

8439-73, Poster Session

Calibration-free 1f and 2f wavelength modulation spectroscopy with background RAM nulling

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This paper discusses the prospects of a recent generic fibre-optic method to eliminate the residual amplitude modulation signals in 1f and 2f wavelength modulation spectroscopy (WMS) and a calibration-free 2f WMS technique for the measurement of gas parameters. In recent years two distinct strategies for calibration-free tunable diode laser spectroscopy (TDLS) has been closely studied with specific focus on industrial applications where the main challenges are the variable gas pressure and beam steering effects that lead to changes in signal strengths for reasons other than changes in the gas parameters. The first method involves the direct recovery of the absolute gas absorption lines using 1f WMS and extraction of gas parameters from it. The ease of signal interpretation makes this approach attractive. The second method recovers the 2f WMS signal and normalizes it by the 1f WMS signal. The line centre value of the 2f signal yields the gas concentration and temperature. For weak absorbance the 1f WMS signal is heavily dominated by the concentration-independent background signal due to the residual amplitude modulation (RAM) of the laser diode and therefore serves as a normalization signal. It should be noted that this technique requires both the 2f and the 1f signals, making it imperative to account for the significant variation of the laser's tuning efficiency (GHz/mA) and the IM-WM phase-shift with the modulation frequency (fm). In both these approaches the RAM signal has been an undesirable signal component in some respect. The 1f RAM due to linear intensity modulation (IM) of the laser tends to limit detection sensitivity in 1f WMS, and leads to signal distortion in 2f WMS. The 2f RAM due to the nonlinear IM is not a major concern in WMS for lasers with highly linear power-current characteristics. The 2f RAM becomes significant if the power-current characteristics are highly nonlinear and the tuning efficiency is low at the chosen fm. A significant level of 2f RAM contributes a background 2f signal that needs to be considered while modeling the theoretical signal. This paper proposes an alternative calibration-free 2f WMS technique that recovers the full, undistorted 2f WMS signal by eliminating the 2f RAM and applying the Phasor Decomposition method, and then normalization by the 2f RAM. The advantage of this strategy is that it operates at a single value of fm and the normalization signal is obtained without having to change the detection harmonic. Using the recently-demonstrated method to selectively eliminate the 1f and the 2f RAM signals, one can first eliminate the background RAM by activating the RAM nulling setup and record the weak absorption-dependent signal with the detection sensitivity maximized, and then obtain the normalization signal by deactivating the setup. The full, undistorted 2f WMS signal can be obtained by eliminating the 2f RAM and applying the so-called Phasor Decomposition method and then normalizing it by the 2f RAM. The advantage of this strategy is that it operates at a single modulation frequency and the normalization signal is obtained without having to change the detection harmonic.

8439-74, Poster Session

In-line optical fiber sensors based on low-loss semi-reflective in-fiber mirrors

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Semi-reflective mirrors are essential constituent parts of many fiber optic sensors, especially Fabry-Perot interferometers (FPI). While a flat-cleaved tip of the optical fiber is frequently used as a semi reflective mirror, it usually requires assemblies that imply structures larger than fiber diameter that further include bonding materials, which are inferior to silica in terms of mechanical and chemical properties. In addition, flat cleaved fiber end only provides fixed reflectance.

In the past TiO2 coating of the flat cleaved fiber end followed by fusion splicing was used to create in-fiber mirror. Laser ablation and wet etching of cavity at the fiber tip followed by fusion splicing has been also reported, but both of these processes imply relatively complex manufacturing and limited control or were not developed to the level which provides sufficient control over mirror final properties.

The presented method of semi-reflective in-fiber mirror fabrication is based on selective chemical etching of the standard single-mode fiber (SMF). The etched fiber is then fusion spliced with flat-cleaved fiber under controlled splicing conditions. Mirror's reflectance can be precisely set in any range between 0.1% and 9.5 %.The extensive research of etching and splicing procedures was performed in order to achieve high repeatability of fabrication process and high optical quality of mirrors in terms of minimum excess losses, which proved to be below 0.25 dB.

The practical usability of produced in-fiber mirrors was evaluated by fabrication of in-line temperature sensor and evanescent field refractive index (RI) sensor.

Temperature sensor is an intrinsic type of in-line FPI, formed between in-fiber mirror and flat cleaved optical fiber tip. The temperature dependence of fiber refractive index defined the optical-path length change of the FPI, which was interrogated by spectrally resolving technique. As an example, we evaluated a 0.77 mm long temperature sensor that was optimized for a temperature range from 0 to 100°C. The optical temperature measurement system showed a temperature resolution better than 0.4 °C and repeatability better than 0.6 °C.

The evanescent RI sensor was performed by splicing of small-diameter SMF between two in-fiber mirrors and additional removing of the intermediate fiber-cladding by chemical etching. When de-claded fiber core is immersed in the measured medium, the effective index of the fundamental mode and, consequently, the optical distance between the mirrors of the in-line FPI depends directly on the measured medium RI. The sensor was as well interrogated by spectrally resolved technique. The highest sensitivity of 830 nm/RIU was measured at RI of 1.444.

8439-75, Poster Session

High concentration measurement of mixed particle suspensions using simple multiple-angle light scattering system

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A simple multiple-angle light scattering system was developed for differential measurement of particle concentrations in suspension even in high concentration where multiple scattering effects are significant based on size. The system combines multiple-angle detection to collect scattered angle dependent light intensities, and Partial Least Square Regression method (PLS-R) to compose the predictive models for analysing scattered signals to obtain concentrations of samples under investigation. The system was designed to be simple, portable and inexpensive. It employs a diode laser (red AlGaInP-based) as light sources and a silicon photodiode as detectors and optical components, all of which are readily available. The technique was validated using 1.1 µm and 3.0µm polystyrene spheres in both mono-dispersed and poly-dispersed suspensions. The measurement results showed good agreement between the measured results and reference values. Their deviations from the reference values are 2.4% and 1.5% relating to references' concentrations of 1.3E8 and 1.2E7 particles/ml for 1.1 um and 3.0 um in mono-dispersed solutions and 2.3 % and 3.5% relating to references' concentrations of 1.1E8 and 4.4E5 particles/ml for 1.1 µm and 3.0 µm in mixed solutions, respectively. This system is a compact but high performance system allowing multiple particle sizes in high concentration to be measured concentration simultaneously.

8439-76, Poster Session

Signal amplification of surface plasmon resonance detection based on a large-area subwavelength dielectric grating

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In this study, we describe the fabrication of one-dimensional subwavelength dielectric nanogratings as a surface plasmon resonance (SPR) sensor platform using nanoimprint lithography (NIL) technique. Large-area dielectric nanogratings are patterned on a 45-nm thick silver film deposited on a SF10 glass substrate via an adhesive chromium layer. In contrast to a conventional SPR sensor system with a flat metallic surface, introduction of dielectric grating patterns with a period of 400 nm and a depth of 100 nm is intended to increase the overall surface reaction area, i.e., the number of ligands and target molecules that participate in the surface reaction, finally achieving the sensitivity improvement.

In terms of fabrication process, unlike conventional lithographic techniques, where nanoscale patterns are defined by the modification of the chemical and physical properties of the resist, NIL is based on the direct mechanical deformation of the resist. Thus, the resolution achievable with NIL is beyond the limitations caused by light diffraction or beam scattering in other optical lithographies. In particular, NIL-based fabrication can be extended into more complex structures, including plasmonic waveguides for the optical interconnection and communication and the microfluidic channels for chemical biosensing and lab-on-a-chip devices. The potential for high precision, mass production, reproducibility, and large scale integration of the plasmonic nanostructures makes NIL considered as the most promising next generation nanopatterning technique.

After the fabrication combined with etching and lift-off processes, a larger-area sensor surface of 5 mm × 5 mm could be obtained. This SPR substrate allows reproducibility of sensor performance and low-cost and high-throughput fabrication of the SPR biosensor chips as well as a high sensitivity. The sensor performance of the fabricated samples is then experimentally measured by a parylene coating which causes a refractive index change on a sensor surface. Experimental results exhibit that subwavelength dielectric nanogratings provide a notable sensitivity improvement, which is attributed to an increase in the surface reaction area. It is also found that the obtained sensitivity enhancement matches well with the numerical analyses based on the rigorous coupled-wave analysis. Our approach could show the feasibility and extend the applicability of SPR biosensor with large-area dielectric nanostructures to diverse biomolecular binding events.

8439-77, Poster Session

Air-bridge high-speed InGaAs/InP waveguide photodiode

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The photodiode (PD) is a key component in optical transmission and optical measurement systems which receive optical signals and convert them into electric signals. High speed, high responsivity, high power and low dark current are desirable attributes of the PD in these applications, but also the simple fabrication for high yield and low cost is necessary for industry production.

Different structural PDs based on materials to optimize for high performance have been reported such as PIN PD, uni-traveling carrier (UTC) PD, modified UTC PD and so on. However, a proper design of the device structure is also very important to reduce the parasitic effect on the performance and to simplify the fabrication process then lower the cost. In our previous work, we have proposed a new effective PD structure in which the GSG pads are designed to simplify the fabrication process by deep isolation etching around the signal Pad and BCB planarization was used to support the bridge connecting the pad and p contact metal on the waveguide. The design worked out prominently except that the BCB step could be time consuming with a very deep trench around the pads so that several layers of BCB spin-coating and curing were needed. In this paper, based on our previous work, an air-bridged device was developed to avoid the BCB problem then further to reduce the process steps. By designing two arms of the bridge with proper angle, the air bridge was obtained easily utilizing the crystal orientation dependent wet etching of InP material in the etchant. Firstly the p metal with bridge and pads metal were deposited by Ebeam, then SiO_2 mask was deposited on metal to be used as mask for dry etching. After waveguide etching, N metal was deposited. finally photoresist was used as mask to protect all the areas except for the bridge part and wet etching was adopted to form the air-bridge.The new structure greatly eased the fabrication processes and increased the yield. In our experiment, the fabricated ridge waveguide devices work robustly with 40GHz bandwidth with InGaAs PIN material .

8439-78, Poster Session

Surface functionalisation of TiO_2 evanescent waveguide sensor for E. coli monitoring

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Surface functionalisation is a very important treatment to ensure that biosensors detect properly bimolecular, protein etc. In this paper, we study the thin film surface functionalisation of a TiO_2 evanescent waveguide sensor and their effect on transmission light for the early detection of ecoli in post colon surgery. TiO_2 is used as waveguide material deposited by atomic layer deposition (ALD) and fabricated using lithography in combination between wet and dry etching (reactive ion etching)[1, 2]. Three layers are used in the functionalisation : the self-assembled monolayer (SAM), the proteins and and the antibodies. Aminopropyltriethoxysilane (APTES) is used as SAM and reacts with -OH group (hydroxyl). Consequently the -OH group must be provided on substrate. In order to have the proper group we deposited on the waveguides a very thin SiO_2 film (10 nm) using PECVD and then treat the samples in an oxygen plasma chamber for around 1 minute to create the OH-groups. Afterward APTES is immediately applied on the surface For reliability every layers of the functionalization process are dropped casted in liquid cell placed above the waveguide. Protein-A the second layer of the functionalisation is put Protein-A on APTES as interlayer then the last layer of antibodies is applied.

Fourier transformation infrared spectroscopy (FTIR) is used to investigate SAM on sample surfaces. The ethoxy moieties of the APTES are around 1440 and 1390 m^{-1}[3]. The light of Superluminescent light emitting diodes (SLEDs) (lamda = 1.3 micrometer, 500 mA) is channelled via an optical into the APTES coated TiO_2 waveguides. The transmitted light is converted by a photodiode and displayed in an oscilloscope. The experiment shows that after applying APTES on top of waveguide a decrease int the transmitted light from 25 to 17 micro Watt. However the flow cell generates loss of signal of 40%.

8439-79, Poster Session

Simulation of surface plasmon fiber optic sensor including the effect of oxide overlayer thickness change

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A theoretical model of a surface plasmon resonance (SPR) fiber-optic sensor based on the theory of attenuated total internal reflection is presented. The analysis of the sensor response is carried out in frame of optics of multilayered media [1]. Some of the studied SPR sensors use an oxide or a semiconductor overlayer for the protection of the metallic layer generating the surface plasmon wave. In the same time, the overlayer can help to improve the sensitivity of the sensor [2]. The overlayer protects the metal against the oxidation, but a native oxide layer can be formed on its top surface when exposed to the atmosphere. This effect has been scarcely addressed, even if it can have an influence on the functionality of the sensor. In our case, the structure contained a metallic layer covered by silicon with a native oxide layer. The influence of the native oxide layer parameters on the sensor performance in wavelength domain is studied in detail. The calculation of optical power transmitted through the multimode sensing fiber is carried out in order to evaluate the response of the SPR sensor. The effect of the dispersion of all involved media is taken into account. The thickness of the layers in the sensing structure have been optimized to achieve the best performance of the sensor in terms of sensitivity and full width at half maximum of the power transmittance minimum.

[1] Ciprian, D., Hlubina, P., Proceedings of SPIE Vol. 8306, 830612 (2011),

[2] Bhatia, P., Gupta B. D., Applied Optics, Vol. 50, Issue 14, pp. 2032-2036 (2011).

8439-80, Poster Session

NIR diode laser-based QEPAS for acetylene detection

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Quartz-enhanced photoacoustic spectroscopy (QEPAS), which uses a tiny quartz tuning fork (QTF) with high Q-factor of ~10,000 even at atmospheric environment to accumulate the generated photoacoutic (PA) pressure and detect it at its resonant mode, is a powerful method for trace gas detection for its high sensitivity, compact size, immunity to ambient noise and easy implement. QEPAS with a near infrared distributed feedback diode laser at 1.53 μm was demonstrated for acetylene detection at atmospheric pressure and room temperature in this report. The P9 line of ν1+ν3 band of C2H2 is selected for light absorption and PA pressure excitation. A resonant tube pairs with optimalized dimension is placed beside the two facets of our quartz tuning fork (QTF) with a small gap for PA signal enhancement. The wavelength of diode laser is modulated at half of the resonant frequency of QTF for second harmonic signal detection. The influence of residual amplitude modulation was also investigated at different measurement mode: wavelength tuning mode, wavelength locking mode and frequency response mode, respectively. Considering the estimated noise level, a minimum detectable concentration limit (1σ) of 2 part-per-million (ppm) was achieved by using a 7-mW laser power with a 1-s lock-in time constant, which corresponds to a normalized noise equavalent absorption (NNEA) coefficient of 5.4×10-8 cm-1 W/√Hz.

8439-81, Poster Session

Design of a demodulation scheme for a hybrid fiber sensor system for composite materials

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Composite material structures are widely used in the aerospace, marine, aviation and civil engineering industries because of their advantages of high strength and stiffness with less weight. Fiber Bragg grating (FBG) sensors are the most widely used sensors for structural health monitoring applications (SHM). FBG sensing is a reliable point sensing technology; but the cross-sensitivity between temperature and strain is a major disadvantage for many practical applications. Polarimetric sensors have also been proposed for use as sensors for structural health monitoring in composite materials. Polarimetric sensing technology in particular is a promising candidate for sensing in composites, for example utilizing Polarization Maintaining Photonic Crystal Fiber (PM-PCF) sensors. We have previously demonstrated the use of both FBG and polarimetric sensors as a hybrid sensing technology for simultaneous strain and temperature measurements in composite materials.

The design and preliminary simulation results for a flexible single substrate demodulation module for a hybrid sensing system based on a polarimetric fiber sensor and a fiber Bragg grating (FBG) for composite structural health monitoring are presented. The demodulation system uniquely allows for the multiple outputs of FBG and polarimetric sensors to be converted to a common optical intensity domain, and hence can be resolved to obtain simultaneous strain and temperature measurements from both types of the fiber sensors. The single demodulation module for the hybrid sensor is comprised of an Arrayed Waveguide Grating (AWG) and an Electro-optic (EO) modulator. Unlike “laboratory-use” demodulation systems which typically do not need a compact form factor, the proposed miniaturized demodulation system is light weight, has low power consumption and meets the requirements of aerospace applications. It has also been designed to allow for the possibility of embedding or attachment to a composite part. The bandpass responses of the AWG are designed to match the peak reflected wavelengths of the FBGs so that the differential wavelength information can be converted to intensity variations recorded by the array of detectors connected to the output waveguides of the AWG. In the polarimetric sensor demodulation section of the system, an electrical control voltage is applied across the electro-optic modulator to phase match the polarimetric sensor output. The magnitude of this voltage provides information about the amount of phase variation that has occurred in the sensor in response to an external stimulus. For fabrication a post-lift-off method is proposed on a common substrate ZPU12/460 and such e flexible demodulation system is immune to small bending and perturbations. A performance optimization is carried out for EO-phase modulator based on a nonlinear chromophore-amorphous polycarbonate electro-optic polymer core having refractive index (RI) 1.612 and a Vπ-voltage <3V is attained. For the AWG band pass filter based on a UV-curable polymer ZPU12/460 (RI=1.466) and core polymer UV15 (RI=1.504) is used and an insertion loss of <10dB is obtained. The proposed demodulation system will have a wide range of applications in structural health monitoring in composite materials.

8439-82, Poster Session

Remote optical fiber sensor based on an LPG sensor head with Raman amplification optimized by numerical methods

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In this work, we analyze a remote optical sensor system based on Raman amplification, composed by one Long Period Grating (LPG) as a sensor head separated by 50 km from the optical source and the interrogation unit composed by two Fiber Bragg Gratings (FBGs) modulated by two Piezoelectrics Transductors (PZTs).

The optical fiber sensor systems are typically limited to operate at distances of only few kilometers due to the attenuation effects and noise present in the optical fiber that adversely affects the broadband signal used in the interrogation units.

Since the active components of the system and the sensor head are separated over such a large distance, it is necessary to consider optical amplification to strengthen the optical signal. The Raman fiber amplifier is the best choice due to the capability to reach the desirable gain bandwidth changing the pump lasers parameters such as the pump power, number of pumps and spectral position. Therefore, this technology is suitable to use in multiplexed sensors system.

We present experimental results and computational models that describe the Raman interaction between the pumps and the sensor signals. The implemented models allow optimizing the remote optical fiber sensor systems in order to measure/monitor the environmental temperature. We show that under Raman amplification the power ratio between the two central wavelengths of the FBG has a linear relation with the change of LPG resonance with the environmental temperature.

8439-83, Poster Session

Demodulation of FBG sensors embedded in a fiber optic Sagnac loop

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The high-power electric systems will fail due to a number of different reasons. Because they are in huge capacities in ultra-high-voltage environments, the failures lead to substantial damages to the societies. To prevent the possible failures and decrease the maintenance cost, it is recommended to have a condition-monitoring sensor system in the power systems to achieve preventive maintenance. For example, the partial discharge (PD) and abnormal temperature variations are the most common symptoms of the failures in large capacity power systems, such as GIS (gas insulated switchgear) or molded transformers. They have done intensive research to detect the PDs and the temperature variations from the inside of the power systems using different sensors.

In this paper, we combined the fiber-optic Sagnac interferometer acoustic sensor and the FBG temperature sensors for the simultaneous measurement of the PD vibrations and the temperature variations. The acoustic sensors are constructed by winding fiber-optic coils around cylindrical mandrels. The FBG sensors are inserted in the fiber-optic Sagnac loop for the quasi-distributed temperature measurement. The signals from the FBG sensors and the acoustic sensor are collected from the single photo-detector which is outside of the Sagnac loop. Although this combination of sensors in one fiber-optic loop provides the simpler and the more cost-effective structure, however, the reflected Bragg wavelengths are mixed with the rest of the light source that passed the FBGs. To separate the FBG sensor signals from the noise, we used a fiber-optic attenuator which is located at an asymmetrical position in the Sagnac loop. By balancing the counter propagating light intensities by using the attenuator, the background noise signals could be suppressed to obtain the FBG sensor signals. Also a tunable wavelength fiber laser was used as the light source for better signal-to-noise ratio than the broadband sources. We constructed the laser by combining a semiconductor optical amplifier and a fiber-optic Fabry-Perot tunable filter. And a fiber-optic variable directional coupler was used as an output coupler to optimize the fiber laser output.

8439-84, Poster Session

The sensitivity improvement of FBG temperature sensor

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In recent years, the FBG (fiber Bragg grating) has been intensively commercialized and used for many sensing applications, especially for the structural health monitoring of large structures. The reflected Bragg wavelength from the FBG changes linearly according to strain and/or temperature variation. Because of this linear wavelength encoding, the FBG sensor output is very robust against electromagnetic noises and harsh environments. When a quasi-distributed sensor system is constructed with multiple FBG sensors, the Bragg wavelength changes can be collected and analyzed with a few demodulation techniques. The measurement resolutions of the existing techniques are fine enough to tell the small Bragg wavelength changes by the small measurand changes, for example the temperature change less than 1 degree. Most of the techniques, however, require expensive parts, complicated structures and calculating algorithms. These make it difficult to use FBG sensors to technically conservative areas, such as high-power electric systems. The FBG sensor has many advantages to be applied for high-power systems such as transformers, GIS (gas insulated switchgear), power cables, etc. These systems need robust, accurate and cost-effective distributed temperature sensor system for preventive maintenance system. It would be great if we can develop a more sensitive FBG. However, the temperature sensitivity of the intrinsic FBG sensor is fixed by the related coefficients. In this paper, we propose to use a length of bi-metal to boost the temperature sensitivity of the FBG sensor. A FBG sensor is attached to a piece of bi-metal which has much larger expansion coefficient than the optical fiber. The Bragg wavelength changes not only by the temperature effect, but also by the strain effect originated from the bi-metal's expansion. The temperature sensitivity of the FBG sensor has increased more than twice of the intrinsic FBGs. The structure of the proposed sensor is quite simple. However, because of the high temperature sensitivity, we can use low-cost demodulation techniques, such as edge filters, matched filters, or diffraction and ccd array detections. And this will enable us to build the low-cost and the simpler sensor systems suitable for high-power electric systems.

8439-86, Poster Session

Monothically integrated GaAs and Si based long-wavelength tunable photodetector

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Ultra-narrowspectral linewidth, wavelength-tunable and highspeed photodetectors are useful for wavelength-demultiplex receiving applications in optical communication. We demonstrated a tunable long wavelength photodetector by using heteroepitaxy growth of InP-based In0.53Ga0.47As-InP p-i-n structure on GaAs based GaAs/AlAs Fabry-Perot filter structure. High quality heterepitaxy was realized by employing a thin low-temperature buffer layer. A wavelength tuning range of 10.0 nm, a quantum efficiency of 23%, a spectral linewidth of 0.8 nm and a 3-dB bandwidth of 6.2 GHz were simultaneously obtained in the device. Moreover, a Si based long wavelength photodetector with the same device structure was also fabricated successfully by using Si/GaAs and GaAs/InP heteroepitaxy. The Si-based photodetector with spectral linewidth of 1.1nm (FWHM) and quantum efficiency of 9.0% was demonstrated.

1.GaAs-based photodetecotor

The epilayers were grown on GaAs (001) substrate using metalorganic chemical vapor deposition (MOCVD) at low pressure (100 torr) in vertical reactor. At first, a Fabry-Perot filter including a bottom mirror, a top mirror and a GaAs cavity layer, was grown on GaAs substrate. Then low-temperature InP buffer layer of 18-nm was grown at 450 and 950-nm InP layer was grown at normal growth temperature of 650°. A 100-nm InGaAsP etching-stop layer was then grown. Finally, layers of p-i-n photodetector were grown, which consist of a 500-nm n-type InP contact layer, a 500-nm InGaAsP spacer layer, a 340-nm In0.53Ga0.47As absorption layer, a 200-nm InP spacer layer and a 200nm p-type InGaAs contact layer. The photodetector was fabricated as the following procedures. Firstly, a 50×50 μm2 top square and 60×70 μm2 bottom rectangle mesas were formed in succession by etching down to the n-type InP contact layer. Secondly, the device was covered with Polyimide and annealed at 210 for passivation. Thirdly, Pt-Ti-Au was evaporated and patterned by a liftoff process. Fourthly, two windows on the InGaAsP etching-stop layer were opened at both sides of the bottom mesa by standard photolithography and wet etching. Pt-Ti-Au was evaporated on the cavity layer as tuning electrode.

2.Si-based photodetecotor

The heteroepitaxy growth of the Si-based wavelength selective photodetector (Si-WSPD) was carried out as follow steps: (1) a 2.3μm GaAs dislocation-filtering-layer (DFL) was grown on a 3° off (100) towards [011] Si substrate by two-step growth and in-situ thermal cycle annealing (TCA). (2) rectangular-mesas on the grown GaAs/Si wafer were fabricated by photolithography patterning and etching in sequence, and the V-groove separating the mesas with width of 50μm and deep of 25μm was formed. After cleaning, the patterned GaAs/Si wafer was loaded into the reactor for re-growth. (3) the GaAs-FPC was grown, after growth of an 1.7μm GaAs layer and in-situ TCA. (4) the InP-PIN was grown on the GaAs-FPC by a conventional two-step growth.

It can be determined that spectral linewidth and peak quantum efficiency is 0.7nm (FWHM) and 25.8%, the broader linewidth and lower quantum efficiency may result from the curvature and residual threading dislocations in the GaAs-FPC.

8439-87, Poster Session

Diffuse-light absorption spectroscopy for beer classification and prediction of alcoholic content

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The brewing process optimization requires innovative methods for automating the monitoring of the most important process and product parameters. Optical spectroscopy has proved particularly effective for online process control and quality sensing. This paper presents the results of a diffuse-light absorption spectroscopy experiment carried out on a collection of 87 beers, 50 of which were selected Belgian beers, while the others were purchased in a supermarket and were produced in Italy, Germany, Denmark, The Netherlands and England. Diffuse-light absorption spectroscopy, performed by means of an integrating sphere, was capable of providing scattering-free absorption measurements - that is, without caring of the natural turbidity of the beer which could impair traditional absorption spectroscopy measurements. In addition to spectroscopy measurements, turbidity and refractive index measurements were also performed, for completing the optical characterization of the beer collection. The visible and near infrared spectra, together with the turbidity and refractive index values were used to create a data matrix which was processed by means of multivariate analysis. This method was capable of predicting the beer alcoholic content, as well as of beer classification according to fermentation method (Lager, Ale, Lambic), to color (Golden, Dark), and to wheat content (Weiss). Since the class can be considered as a beer identity, this method is also useful for product authentication or fraud detection.

8439-89, Poster Session

An etched fiber optic vibration sensor to monitor the simply supported beam

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A single mode fiber optic vibration senor is designed and demonstrated to monitor the vibration of a simply supported beam. A reduced clad telecommunication fiber is used to sense the vibration. A rectangular plate (length 30.8 cm, width 2.5cm and thickness 0.5mm) made of spring steel is arranged as simply support beam and is made to vibrate periodically. To sense this vibration a standard telecommunication fiber is chemically etched such that its diameter reaches 50µm and is embedded using an epoxy at the centre of arranged spring steel plate. A Light (1550nm) is launched into one end of the centre etched fibre through a circulator and a FBG is connected on other end. The light reflected by the FBG is transmitted into the same etched fibre and is detected by photodiode connected to a transimpedance amplifier through the circulator. The electrical signal is logged by a computer through NI-6016 DAQ. The sensor works on transmission power loss due to the mode volume mismatch and flexural strain (field strength) of the fiber due to the macro bending in the fiber with respect to the bending of the spring steel. The plate is made to vibrate and the corresponding intensity of light is recorded. Fast Fourier transform (FFT) is used to measure the frequency of vibration. The result shows sensor can sense low frequency of vibration of the beam accurately and a high repeatability also observed during constant vibration of the beam. The sensor has high linear response to axial displacement of about 1mm with sensitivity of 30mV/10µm strain. This low-cost sensor is added advantage that may find a place in industry to monitor the vibrations of the beam structures and bridges.

8439-90, Poster Session

Development of high-sensitivity pressure sensor using reduced clad FBG

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This study focused on the development of high sensitivity pressure sensor based on reduced clad FBG encapsulated in a stainless steel cylinder partially filled with silicon rubber. The sensor works by means of transferring radial pressure into an axially stretched- strain along the FBG. The experiment is carried out using two different FBG's have core/clad diameters of 9/125µm (FBG1) and 4/80µm (FBG2) respectively. FBG2 is chemically etched to reduce the cladding diameter which significantly enhances the pressure sensitivity. The shift of the Bragg wavelength in response to applied pressure is monitored with an optical spectrum analyser (OSA). The measured pressure sensitivity of FBG2 and FBG1 are 5.85 x 10-2 MPa-1 and 2.07 x 10-2 MPa-1, which are approximately 18870 and 6677 times higher than that can be measured with a bare FBG respectively. A very good linearity is observed between Bragg wavelength and pressure. This compact, low cost and robust design of the sensor is expected to find applications in the area of low and medium pressure measurement.

8439-91, Poster Session

Polarization dependency in metal oxide coated tilted FBG refractometers

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Tilted fiber Bragg gratings (TFBGs) present a refractive index modulation blazed by a few degrees in the plane perpendicular to the optical fiber axis. This results in two kinds of couplings: the self-backward coupling of the core mode and numerous backward couplings between the core mode and the cladding modes. TFBG transmitted amplitude spectra are therefore characterized by several tens of cladding mode resonances that possess their own sensitivity to the surrounding refractive index (SRI). TFBGs naturally allow the realization of refractometers accurate to 10-4 RIU (refractive index unit) in the SRI range between 1.33 and 1.45 (refractive index of silica). Recently, it was reported that adding a polymer or porous coating around the TFBG surface extends its sensitivity to SRI values above 1.45.

In this work, we demonstrate that a dense thin film of metal oxide deposited on the TFBGs tightly modifies their transmitted amplitude spectra. While the wavelength difference between orthogonally polarized modes in nude TFBGs remains within a few picometers, the association of a nanoscale metal oxide coating increases this difference up to 500 picometers. This results in two main assets: the sensitivity is extended to SRI values above 1.45 while the strong polarization dependency makes the demodulation process easier.

In our experiments, the TFBGs were written in hydrogen-loaded single-mode standard optical fibers by means of the phase mask technique at 244 nm. The metal oxide coating (ZnO in this case) was deposited by RF sputtering in two steps, with the fibers rotated by 180° after the first deposition. Thicknesses ranging between 100 nm and 400 nm were investigated. For the measurements, an optical vector analyzer and a linear polarizer were used to control the input state of polarization.

8439-92, Poster Session

Volatile organic compounds detection with tilted fiber Bragg gratings coated by ZnO nanoparticles

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This paper presents a sensor based on a Tilted Fiber Bragg Grating (TFBG) covered with a microporous coating consisting of ZnO nanoparticles for the detection of volatile organic compounds.

A Fiber Bragg grating is a periodic and permanent modulation of the core refractive index along the optical fiber axis. This modification is generally obtained by exposing the core of a photosensitive optical fiber to an intense UV interference pattern. A fiber Bragg grating acts as a selective mirror in wavelength around the so called Bragg wavelength.

TFBGs are Bragg gratings that are tilted by a small angle inducing a coupling between the forward-going fundamental core mode and the backward-going cladding modes. They present a transmission amplitude spectrum consisting of several tens of resonances, which present their own sensitivity to the surrounding refractive index. They naturally yield refractometers accurate to 10-4 RIU (refractive index unit).

Specific sensors can be built by using TFBGs covered with a dedicated coating that changes its refractive index when in contact with target chemical species. In that framework, we demonstrate here the possibility to detect ethanol with the help of a microporous ZnO coating whose refractive index changes due to the gas adsorption on the ZnO particles. ZnO was chosen because of its affinity for ethanol combined to its high refractive index (1.9) yielding a porous layer with suitable density.

In this work, the gratings were fabricated into hydrogen-loaded single mode standard silica fibers with UV laser light at 244 nm. The external tilt angle was set to 6°.

ZnO nanoparticles were synthesized thanks to the reaction of zinc acetate with trimethyl amine hydroxide in dimethyl sulfoxide. A suspension of nanoparticles (grain size= 20 nm) in ethanol was obtained and used to cover by dip coating the TFBG with a transparent 10 µm thick layer.

The exposure to ethanol vapors of the covered TFBG yields important modifications of the transmission amplitude spectrum in the range 1510-1590 nm. All the cladding mode resonances show a red shift while their peak-to-peak amplitude decreases with increasing ethanol concentration in air. The response, defined as the amplitude or the wavelength change of a resonance peak as a function of the ethanol concentration, is fast (1s), linear, reversible and without hysteresis (red shift of 60 pm/vol% ethanol and -3.3 dBm/vol% at 1550 nm).

8439-93, Poster Session

Optimisation of the design of fibre optic pH sensor based on layer-by-layer coating

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PH sensors are one of the most researched types of sensors due to the importance of pH measurement in both scientific research and industrial applications. In this paper, the design of a fibre optic pH sensor based on coating built by electrostatic interaction is presented. Different approaches have been applied to functionalise a fibre for pH sensing purpose for example sol-gel and covalent immobilization. For all developed sensors, the pH is estimated through intensity-based measurement. The sensor presented in this abstract, on the other hand, is based on wavelength change with pH. This allows a sensor reading independent of source variation or any perturbation other than pH change.

The 'Layer-by-Layer' (LbL) deposition technique which is based on the electrostatic attraction of opposite charges is one of the most frequently utilized methods for preparing multilayered thin films on different substrates. The technique is based on the alternate dipping of a charged substrate into cationic and anionic solutions.

In this study, this technique is employed with brilliant yellow as a pH indicator and poly (allylamine hydrochloride) [PAH] as cross-linker. The multilayer coating is deposited on an uncladded silica fibre. The designed sensor presents a very good wavelength shift, therefore sensitivity, for a pH range from 6.8 to 9.

Many parameters, such as fibre core diameter, shape (straight and U-bend); and the thickness of the deposited layers (number of layers and the concentration of the indicator solution) have been varied to optimise the design of the pH sensors. The results shows, the sensitivity is inversely related to number of bilayers, core diameter and the concentration of the indicator solution while the U-shape probes show more sensitivity in compare to the straight probes.

8439-94, Poster Session

Plasma surface reflectance spectroscopy for non-invasive and continuous monitoring of extracellular component of blood

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[Introduction] For extracorporeal circulation therapies, hematocrit, hemolysis, and thrombosis should be continuously monitored to prevent anemia, infection, infarction, and to detect any early malfunction of the cardiopulmonary devices. Visible or near-infrared spectroscopy would be useful for the non-invasive diagnosis of blood. However, interpretation of the measured spectrum is complicated because in the conventional measurement methods, photons propagate both extracellular (plasma) and intracellular (red blood cells: RBCs) components. Therefore, the signal is affected by the both changes. To achieve the quantitative optical non-invasive diagnosis of blood, the instrumental technique to extract extracellular (plasma) spectra from that of whole blood was developed. The developed plasma surface reflectance spectroscopy (PSRS) would be useful for the calibration method and the non-invasive diagnosis of plasma without centrifugation.

[Materials and Methods] Fresh porcine blood obtained from a local slaughter house was used. The continuous blood flow was generated by a centrifugal blood pump. The oxygen saturation was maintained 100% by an oxygenator. The diameter of the circuit tubings was 1/4 inch. The circuit flow rate was adjusted at 2L/min. The developed glass optical flow cell was attached to the outlet tubing of the oxygenator. The halogen lamp including the light from 400 to 900 nm wavelength was used for the light source. The light was guided into an optical fiber. The light emitted by the fiber was collimated and emitted to the flow cell flat surface at the incident angle of 45 degrees. The light just reflected on the boundary between inner surface of the flow cell and plasma at 45 degree was detected by the detection fiber. The detected light was analyzed by a spectralphotometer.

[Results and Discussion] Above 600nm wavelength, the spectrum was changed with respect to the changes in the hematocrit. However, the obtained spectrum from 400 to 600nm wavelength was not changed by the changes in the hematocrit. In contrast, the signal in the spectral range was changed when the plasma free hemoglobin increased. The spectral change is very similar with molecular extinction spectrum of hemoglobin. By using two spectral range, 505±5 nm and 542.5±2.5 nm, the differential spectrum was correlated with the plasma free hemoglobin at the correlation factor R2=0.99. On the other hand, as for the change in the hematocrit, the differential spectrum was not correlated at R2=0.01. Finally, the plasma free hemoglobin was quantified with the accuracy of 22±19mg/dL. The result shows that the developed PSRS can extract the plasma spectrum from flowing whole blood. In the spectrum range blow 600nm, the transmitted light into blood is almost eliminated due to high absorption by RBCs so that the developed PSRS can extract the light just reflected the plasma surface.

[Conclusion] The developed PSRS can non-invasively and continuously extract the extracellular spectrum from flowing whole blood. This technique would be useful for the non-invasive diagnosis of plasma without centrifugation and the calibration for the intracellular diagnosis such as hematocrit and oxygen saturation.

8439-96, Poster Session

200 ps FWHM and 100 MHz repetition rate ultrafast gated camera for optical medical functional imaging

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The paper describes the realization of a complete optical imaging device to study brain activation by time-resolved, spectroscopic diffuse optical tomography. The entire instrument is assembled in a unique setup that includes light sources, a ultrafast time-gated intensified camera and all the electronic control units. The light source is composed of four near infrared laser diodes driven by nanosecond electrical pulse generators working in a sequential mode at a repetition rate of 100 MHz. The resulting light pulses, at four wavelengths, are 60 ps FWHM. They are injected in a four-furcated optical fiber ended with a frontal light distributor to obtain a uniform illumination spot directed towards the head of the patient. Photons back-scattered by the subject are detected by the intensified CCD camera; there are resolved according to their time of flight inside the head. The very core of the intensified camera system is the image intensifier tube and its associated electrical pulse generator. The ultrafast generator produces 50 V pulses, at a repetition rate of 100 MHz and a width corresponding to the 200 ps requested gate. The photocathode and the Micro-Channel-Plate of the intensifier have been specially designed to enhance the electromagnetic wave propagation and reduce the power loss and heat that are prejudicial to the quality of the image. New materials are used to decrease the electrical skin effect that occurs at such a high frequency operation. The whole instrumentation system is controlled by an FPGA based module. The timing of the light pulses and the photocathode gating is precisely adjustable with a step of 10 ps. All the acquisition parameters are configurable via software through an USB plug and the image data are transferred to a PC via an Ethernet link. The compactness of the device makes it a perfect device for bedside clinical applications.

8439-97, Poster Session

Elaboration of fluorescent sensitive coatings for gas chemical sensors

by the sol-gel process

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Gas chemical sensors offer a great number of advantages in comparison with the classical methods used nowadays in order to measure the concentration rate of various pollutants in the atmosphere. Their miniaturization, their ease of use and their low cost explain the growing interest in these sensors since several years. This interest is strengthened by the actual context of regulation controls and civilian safety (terrorist threat).

Gas chemical sensors working depends on the sensitive material. Its heterogeneous interaction with the target molecule leads to the modification of one or several of its physicochemical properties (mass, electrical conductivity, optical property...) which is then converted into an exploitable signal via an appropriate transduction system. The device performances are mainly dependent on the sensitive material in terms of sensitivity, reversibility, time stability and stability to climatic conditions.

No simple material can correctly satisfy all these requirements simultaneously. Hybrid sol-gel materials offer the possibility to integrate different functionalities within one system.

Therefore, they represent an interesting alternative for the elaboration of sensitive materials specifically designed for atmospheric pollutants detection.

An example of development of a functionalized silica-based sensitive mesoporous film for the detection of nitroaromatic compounds is presented to illustrate this application.

8439-98, Poster Session

Comparison of macrobend seismic optical fiber accelerometer and ferrule-top cantilever fiber sensor for vibration monitoring

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We present the application and comparison of a macrobend seismic optical fiber accelerometer and ferrule-top cantilever fiber sensor for long distance vibration monitoring utilizing typical telecommunication optical transmission systems including optical fibers, transmitters and receivers. There is a great interest in chemical, petrochemical industry, gas distribution lines and other high explosion risk environments for machines and equipment vibration measurement and online monitoring. Use of telecommunication optical systems allows developing cost-effective monitoring and sensing architecture. All-optical fiber sensor do not create any fire hazard due to the use of low power light source and lack of electric driven parts in sensing part. Optical fiber macrobend seismic sensor consists of single mode optical fiber bended into a loop of radius around few millimeters with attached small seismic mass around 0.3 grams. In the bent region the coupled mode field is shifted due to the effective refractive index change across the fiber. This leads to the coupling to the cladding modes and radiation of light outside the fiber. We achieve signal that is proportional to the geometrical deformation of the loop. Seismic mass is acting through inertia forces on the loop and causes deformation. This allows for measure inertial force and acceleration of the seismic mass. The ferrule-top cantilever (made by Optics11 - Amsterdam, Netherlands) optical fiber sensor is fabricated on a rectangular 3 mm x 3mm x 7 mm glass ferrule equipped with a central borehole and laser curved cantilever with dimensions of 200 microns wide, 30 microns thick and around 3 mm long. After fabrication, an optical fiber is inserted into the hole and glued in. Connected through fiber coupler it can detect bending of the cantilever. Both optical fiber sensors in this setup measure force and acceleration similar to the piezoelectric accelerometers. One of the advantage of this devices is insensitivity to electromagnetic interference because of all-optical head. In this paper we compared parameters and measurement capabilities of both sensor types.

8439-13, Session 3

Development of fiber optic ferrule-top cantilevers for sensing and beam-steering applications

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Ferrule-top cantilevers are new generation of all optical micromechanical sensors obtained by carving microstructures on the top of ferrule terminated fibers. In this talk, we will demonstrate how the combination of plug-and-play interferometric readout with all-optical mechanical actuation can be used for the development of a new generation of sensors and actuators for harsh environments, where commercially available devices would be prone to failure.

Ferrule-top sensors can work in two main modes - static and dynamic. The static mode is based on recording elastic deflection of the cantilever; the dynamic mode relies on tracking changes in its mechanical properties (resonance frequency, quality factor). Depending on the application, one can choose which mode is most suitable or combine both to achieve

best performance. During the talk we will illustrate the relation between specific measured quantity (humidity, pressure, flow) and the behaviour of the sensor. We will further show that the sensor can be actuated using light, giving the possibility to excite the cantilever without any electronics on the sensing head. Finally, we will demonstrate that this light excitation method not only allows to excite the sensor at resonance frequency, but also provides enough power to bend the cantilever statically over few microns by means of local heating. This technique can by use for the development of fully optical beamsteering microdevices.

8439-14, Session 3

Optical fiber sensor for pressure measurement based on elastomeric membrane and macrobending loss

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We propose a fiber optic sensor array based on bend loss assessed by optical time domain reflectometry (OTDR). By using suitable couplers, the link of sensors can be set in a way that each sensor stage is completely independent of each other. The sensor mechanism is based on optical fiber bending loss compressed by external pressure. Due to its implementation simplicity, bending loss sensor (BLS) is probably one of the first conceptions of fiber optic sensor. However this characteristic brings about many low costs interesting applications. The propose sensor measure external pressure by monitoring reflected power from OTDR pulses which attenuate due to fiber bended for external pressure. An elastomeric surface is applied to the sensor in order to communicate external pressure to the fiber coil and also, this make sensor able to deal with degradation coming from aggressive environments. Thanks to the elastomeric membranes available, the sensing system proposed is able to monitor liquid or gas pressure in different kinds of environments, such as water, oil, alcohols, some diluted acids and others, depending only of elastomeric membrane choice. In order to protect the whole sensor and to give it robustness against environmental degradation, an appropriate plastic packaging was chosen. An empirical formula for loss calculation in bent fiber has demonstrated satisfactory results with practical situation, authors considered the bend loss dependence related with physical parameters such as input wavelength, loop radius curvature, number of turns of the bent fiber and, also the bending angle. Bend loss measurements was taken by considering all those parameters. This long for the best parameters in the sensor construction. The specific case of the sensor applied to water percolation monitoring from embankment damns is detailed in this paper. As the experimental measurements presented in this paper were taken in terms of meters of water column it is already a correct unity to measure pressure. Despite the physical quantity called pressure be measured in Pa at the SI units, results provide, at the same time, pressure and water lever percolation information. For this application the sensor array have a number of at least six stages totally independent each other, in such a way that each stage can be developed to monitor a specific environment. In order to reproduce a typical situation of sensor's use, a 6 m tall tube filled with water was installed it the laboratory. A marked fiber optic cable allowed knowing the correct depth of the sensor. In this configuration, two groups of measurements were performed in order to reproduce common applications. Sensor link have shown good performance in field tests, reaching work range from 0.1 to 0.6 atm with 0.05 atm precision.

8439-15, Session 3

Monitoring of gamma-irradiated Yb-doped optical fibers through pump-induced refractive index changes

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We propose new method that allows to monitor formation of color centers in Yb-doped fiber under γ-radiation. The method is based on the refractive index changes effect. In our experiment four identical samples of the single-mode aluminum silicate Yb-doped optical fiber have been γ-irradiated with different doses from a 60Co source. All fibers passed the test in the intereferometric setup for the pump induced RIC effect. During the test the phase shifts induced in the fiber by 1-ms-square pump pulses at 980 nm were recorded with a testing signal at ~1.53 µm. The phase traces normalized to their maximum values highlight the differences in their growing and decaying part to be in correlation with the fiber irradiation doses. For non-irradiated fibers decay parts are perfectly fitted by one exponential function with the relaxation time constant equal to the Yb-ion excited state life-time ~750 µs, the same for all fiber samples. However, for irradiated fibers the similar fitting gives a triple exponential decay with time constants estimated to be ~750, ~500 and 40µs. For higher irradiation dose the difference is more strengthen. Having in mind that the obtained difference in phase shift dynamics could be associated with excitation of some color centers induced in the fiber matrix by γ-irradiation, we represent the normalized phase shifts as a superposition of two contributions. The first is due to excitation of Yb-ion, to be the same for all tested samples, the second is due to excitation of color centers. The amplitude of the second part highlights degree of fiber degradation under γ-radiation and is directly proportional to the concentration of the excited color centers that linearly grow with the irradiation dose. This work was supported by ERDF-WR (Mediatic project), IAP VI/10 of the Belgian Science Policy and the program of RFASI.

8439-16, Session 3

Gold-coated optical fiber micro-tapers for sensor applications based on the surface plasmon resonance effect

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The use of optical fibers for SPR sensing was first reported by Jorgenson and Yee in 1993. Since then, a large number of sensors based on multimode or singlemode fibers have been proposed. In order to gain access to the evanescent fields of the guided fiber modes, which are essential for excitation the SPW's, different methods have been realized. These methods mostly aimed at removing the cladding layer for a well-defined length, by means of chemical etching, burning off by flame or mechanical polishing. Another promising method is the use of tapered fibers. In a tapered fiber, the reduction of the core and cladding diameter causes the evanescent fields to spread out into the cladding, and for certain taper waist diameter, it can reach the outer boundary. When a thin metal film (Ag or Au) is deposited on the surface of the taper waist, surface plasma waves can be excited by the guided fiber modes. These waves propagates along the interface between metal and surrounding medium.

If the metal film deposited uniformly around the fiber, these devices show no dependence with the polarization of the incident light. In the other case where planar metal layers are used (e.g. on side-polished fibers), a defined incidence of p-polarized light is necessary.

Until now, only few fabrication techniques of metal deposition onto a fiber taper waist for SPR excitation have been reported in the literature. In the most case the taper waist was deposited from one side or two opposite sides resulting in one or two layers with a semi-cylindrical shape onto the fiber. Also a three-step sequential deposition process has

been described. In these cases, the lack of circular geometry permitted the excitation of several surface plasma waves. Thus, the transmission spectra of these devices show more than one resonance dip.

To produce a fully symmetric deposition that covers the whole circumference of a fiber section uniformly, the few setups described in the literature are based on rotating a fiber. But the authors mentioned that the minimal taper diameter that their setup can handle is about 20 µm. In this paper we present a novel fully symmetrical deposition method, based on sputtering technique and usage a gold-ring target. By means of this method we were able to produce a homogenous gold film thickness around the taper waist over a length of 2-3 mm,also for taper diameter smaller than 20 µm. The advantage of smaller taper diameter is the increasing of the refractive index sensitivity of the sensor device.

We present numerical calculations on the effects of the taper waist diameter, gold film thickness, additional buffer layers and analyte interaction length on the plasmon resonance wavelength spectrum. The sensitivity on analyte refractive index and adsorption of bio layers is investigated. Modelling results are compared with experimental data from gold-coated fiber-micro-tapers as sensing element.

8439-17, Session 3

Monte Carlo simulation of surface plasmon polariton excitation on U-bent multimode optical fibers

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Monte Carlo (MC) approach is applied to simulate and analyze the conditions necessary for Surface Plasmon Polariton (SPP) excitation on a thin and narrow gold strip placed at a core/cladding interface of a U-bent multimode optical fiber (MOF). The physical model used to describe propagation of photons within the system is based on ray approximation combined with the selected results of wave optics and the classical Drude's theory of metals. Thus, because of the model simplicity, relatively large photon statistics can be used in MC simulations to test possible influence of variety of parameters (such as the photon energy, core/toroid radius ratio, core and cladding refractive index, and gold strip thickness and its position along the semi-toroid) of the system on its light transmission and emission characteristics. The necessary computer code is assembled and the calculations performed within the Mathematica (Wolfram Research) simulation environment. The obtained results provide valuable guidelines for design of optrodes exploring SPP resonant excitation on Ubent MOFs.

8439-18, Session 3

First demonstration of a 12 DFB fiber laser array on a 100 GHz ITU grid, for underwater acoustic sensing application

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Underwater fiber laser hydrophone, consists of an optically pumped narrow-linewidth distributed feedback fiber laser (DFB FL), which is exposed to acoustic pressure, producing laser frequency fluctuations that are interrogated using an unbalanced interferometer [1].The resolution of this type of sensors is only limited by the intrinsic frequency noise of the laser. DFB FLs are particularly suited for compact hydrophones array due to their low diameter hydrophone capability and simple multiplexing capability when they are in series on a single fiber [2, 3]. However cascading them may create unwanted external optical feedback in each laser cavity. These external reflections from the side lobes of adjacent Bragg gratings and from Rayleigh scattering in the connecting fiber result in excess intensity and frequency noise as well as occasional self-pulsing [4, 5].

A system based on 16 DFB FL and spectrally separated by 200 GHz has been mentioned in the literature [6]. In this paper, we demonstrate for the first time the multiplexed array of 12 distributed feedback fiber lasers (DFB FL) on a single optical fiber, separated by only 100 GHz (0.8 nm) in the C-band. These lasers are pumped by a 200 mW laser diode at 1480 nm with no apparent impact on the sensor noise floor despite the fact that the residual reflections from adjacent gratings may be enhanced due to the smaller wavelength separation. Each DFB FL, especially developed for serial multiplexing, exhibits low lasing threshold between 1 and 2 mW, low intensity noise and very low frequency noise (less than 30 dB Hz^2/Hz at 1 kHz from optical carrier). From these experimental results, extension to 32 DFB FL array (on 100 GHz ITU grid) multiplexed on one fiber will be discussed.

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REFERENCES

1. Foster, S., Tikhomirov, A., Milnes, M.,Vetzen, J.V. and Hardy, G., "A fibre laser hydrophone", Proc. SPIE 5855, 627-630 (2005).

2. Cain, T., Hodder, B. Jones, D., Bedwell, I., Boggis, H., Mercer, D., Foster, S., Tikhomirov, A., Goodman, S., "Fibre Laser Sensors for Underwater Acoustic Surveillance Arrays", Proc. of Undersea Defence Technology Pacific Conference, Australia, 2008.

3. Bedwell, I.R. and Jones, D.R., "Fiber laser sensor hydrophone performance", Proc. of IEEE OCEANS 2010 conference, Sydney, 2010.

4. Tikhomirov, A. and Foster, S., "DFB FL sensor cross-coupling reduction", J. Lightw. Technol. 25, No. 2 (2007).

5. Ronnekleiv, E., Hadeler, O. and Vienne, G., "Stability of an Er-Yb-doped distributed-feedback laser with external reflections", Optics Letters 24, No. 9, 617-619 (1999).

6. Foster, S., Tikhomirov, A., Englund, M., Inglis, H., Edvell, G. and Milnes, M., "A 16 channel fibre laser sensor array", Proc. Opt. Fiber Sens. OSA Tech. Dig., 2006, Paper FA4.

8439-19, Session 3

DFB laser-based electrical dynamic interrogation for optical fiber sensors

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An electrical dynamic interrogation technique previously reported by the authors for long-period fiber grating sensors is upgraded following an approach relying exclusively on the modulation of a DFB Laser.

The analysis of the detected first, second and third harmonic generated by the electrical modulation of the DFB laser allow us to generate an optical signal proportional to the LPG spectral shift and resilient to optical power fluctuations along the system.

This concept permits us to detect different environmental parameters attenuating the effect of the 1/f noise of the photodetection, amplification and processing electronics on the sensing head resolution.

The developed interrogation architecture is simple, allows multiplexing of several sensing heads, and can be appliedd for the interrogation of optical fiber structures directed to the measurement of DC or quasi-DC measurands, as is the case of multimode interferometers (MMI) or other sensing devices based on the phenomenon of surface plasmonic resonance (SPR).

8439-20, Session 3

A novel highly birefringent fiber loop mirror using a 3×3 coupler

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In this work, the authors present a novel high birefringent (Hi-Bi) fiber loop mirror using a 3×3 coupler. Due to the six arms of the coupler, the configuration presents two loop mirrors, one of them is in transmission and the other is in reflection. The sensing head is located in the reflection loop and it is formed by a section of Hi-Bi elliptical core fiber. The transmission loop mirror is closed with a splice between both arms. The spectral response of this configuration presents two different interferences which can be distinguished and changed by the polarization controller. When a single interference is observed, it can be considered as a conventional Hi Bi fiber loop mirror. Finally, the two interferences are generated by the phase difference created by the transmission loop mirror. The sensing head characterization is done for temperature and strain measurements. The sensitivities obtained are 0.23 nm/ºC and 2.6 pm/ for temperature and strain, respectively. It is noticed that the sensitivities are practically the same for the two interferences. Future work consists on the exploration of the transmission loop to interrogate the sensing head, providing elimination of the phase fluctuations that can occur, increasing its potential for remote sensing applications.

8439-21, Session 3

Design of a mechanical transducer for an optical-fiber accelerometer based on polarization variation

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This paper presents the design of a mechanical transducer for a new kind of optical-fiber accelerometer based on polarization variation. The working principle is the following. Polarized light goes through an optical fiber which is deformed by a mechanical transducer proportionally to the acceleration undergone by the latter. This deformation modifies the birefringence within the fiber, altering the polarization state of the light. The light goes through the transducer, a polarizer and finally arrives at a photodiode. Thanks to the polarizer, the optical power at the photodiode varies if the state of polarization before the polarizer does. If the mechanical transducer vibrates the final optical power will then have a constant part and a variable part varying at the same frequency as the transducer. The use of birefringence to measure vibration was already tested [Zhang and Bao,Optics Express 16,10240 (2008)] but the tests focused on the optical side of the sensor, the fiber being simply coiled around a piezoelectric stretcher inducing the deformation. For industrial applications an actual mechanical transducer has to be designed to convert the mechanical vibration into fiber deformation. Several transducers can be imagined using either bending, twist, stretching or crushing of the fiber. This can be achieved by the use of beams deforming a fiber fixed to it or in the case of bending by a mass attached to a stretched fiber. Those different excitations are analytically compared to know which one has the maximal sensitivity. The analysis uses the Euler-Bernoulli thoery of beams and the mechanics of materials to determine the stresses within the fiber and then the photoelasticity theory to determine the stress induced birefringence. However the sensitivity of an accelerometer based on the deformation of the sensing device is dependent on the resonant frequency of the system. The higher the sensitivity the lower the resonance. In order to have comparable results, curves are drawn showing for each possible transducer the evolution of the sensitivity in function of the resonant frequency. It turns out that the use of crushing shows a sensitivity several orders of magnitude higher than the other deformations. In the case of crushing, experimental results confirmed the analytical computation of the sensitivity.

8439-22, Session 3

Ellipsometry with an undetermined polarization state

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We show that, under the right conditions, one can make highly accurate polarization-based measurements without knowing the absolute polarization state of the probing light field. It is shown that a stationary polarization state of light, passed through a material in which the size of the birefringence randomly varies has a well-defined and preserved orbit on the Poincare sphere. Changes to the orbit can then be used in place of the absolute polarization states to measure the optical properties of a sample under investigation. We illustrate the usefulness of using this fixed orbit as the probing polarization state (referred to as a generalized polarization state) by demonstrating fiber-based ellipsometry.

In our experiments, the varying birefringence was obtained by stressing the polarization maintaining (PM) fiber through heating and bending. We performed fiber-based ellipsometry by placing the PM fiber and coupling optics between the polarizer and sample. While the light reflected from the sample was analyzed to obtain the Stokes vector components. The orbit is projected onto a plane in the Stokes vector space, to form an ellipse. The ellipsometry parameter Δ is obtained by measuring the rotation of the ellipse due to reflection from the sample, while is obtained by measuring the change to the ratio of the major and minor axes of the ellipse.

We will show, both experimentally and through modeling, that the output polarization states of the PM fiber form a circular orbit on the Poincare sphere and that this orbit is rotated on the Poincare sphere after reflection from a sample. We will show the effectiveness of this approach by presenting ellipsometry results, where sub-nanometer layers of carbon, are detected with accuracy comparable to that of a conventional ellipsometer.

8439-23, Session 4

Design and integration of vision-based navigation sensors for unmanned aerial vehicles navigation and guidance

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In recent years, the use of Unmanned Aerial Vehicles (UAV) in civil and military applications has increased considerably as they provide cost-effective alternatives to manned flights. UAVs have higher maneuverability, longer endurance and less risk to human life compared to manned systems. They generally rely on Global Positioning Systems (GPS) and Inertial Navigation Systems (INS) for platform navigation and and guidance. However, advancements in computer vision and the development of Vision-Based Navigation (VBN) sensors are playing an important role in the development of UAVs. VBN can be used as an alternative to the traditional GPS/INS to provide autonomous navigation. The required information to perform autonomous navigation can be obtained from cameras which are compact and lightweight sensors. This reduces the number of sensors installed on UAVs where weight is tightly constrained.

In this paper, an innovative VBN system for UAV is presented. Our research concentrates on the precision approach and landing phases of flight (safety-critical flight tasks). Various techniques for VBN are compared and the appearance-based navigation approach is selected for implementation. The approach for estimating the relative position of the runway uses image registration against a set of previously sampled and stored key images. These ordered key images taken along the glide path constitute the visual path for the landing of UAV. Feature extraction and optical flow techniques are employed to estimate the flight critical parameters such as roll angle, pitch angle, deviation from the runway and the body rates. Kalman filtering is used to minimize the errors and a visual servoing system using Fuzzy Logic and a PID (Proportional, Integral, Derivative) controller is designed to control a the dynamics of a real UAV (“Aerosonde” class UAV).

8439-25, Session 4

Tilted pressure-tuned field-widened Michelson interferometer for high spectral resolution lidar

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High spectral resolution lidars (HSRLs) designed for aerosol and cloud remote sensing are increasingly being deployed on aircraft and called for on future space-based missions. The HSRL technique relies on spectral discrimination of the atmospheric backscatter signals to enable independent, unambiguous retrieval of aerosol extinction and backscatter. A tilted pressure-tuned field-widened Michelson interferometer is proposed to achieve the spectral discrimination for an HSRL system at NASA Langley Research Center. The Michelson interferometer consists of a cubic beam splitter, a solid glass arm, and a sealed air arm. The spacer that connects the air arm mirror to the main part of the interferometer is designed to optimize thermal compensation. The pressure of the sealed air arm air can be accurately controlled such that the frequency of maximum interference can be tuned with great precision to the transmitted laser wavelength. In this paper, the principle of the tilted pressure-tuned field-widened Michelson interferometer for high spectral resolution lidar is presented. The pressure tuning rate and the manufacturing requirements are also given. Additionally, challenges in building the real instrument and initial experiment result of the field-widened Michelson interferometer are discussed.

8439-26, Session 4

Automatic detection of small debris on airport runways using a simple innovative long-range optical-based solution

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Airports have to inspect several times a day their runways to prevent incidents due to debris, like the one which occurred in 2000, in Gonesse, when a Concorde plane crashed because of a titane blade on the runway that bursted a tyre. Such incidents are not rare: they happenned once every two years on average between 1980 and 1990, fortunately not with such dramatic consequences. Today, this inspection, which is obligatory since 2008, is done manually by people driving on the runways, which is both expensive (flights have to be disrupted), and unreliable (the runways are inspected only a few times per day). That is why airports would like to have an automatic system which could watch the runways continuously.

Several studies have been carried out to build such a system, mainly in the radar field. But those systems are very complex and invasive because they use many sensors along the runways. Furthermore, they are not sensible to plastic or rubber debris, and can cause problems due to electromagnetic compatibility.

We propose a new, full-optical passive system concept, which will detect debris from the control tower, called DROP (for Détection Robotisée d'Objet sur Pistes d'atterrissage / Robotised detection of objects on runways). It combines a high-performance,optical-mechanical device (in particular a top notch Camera called OCAM^2) with dedicated, optimized and fully automatic post-processing routines.

The main difficulties the system has to manage are the atmospheric turbulence, the always varying photometry of the scenery, and the mechanical stability of the system.

After being intensively studied through complete end-to-end simulation, the first experimental results have been obtained both in labs and in the field (at Marseille-Provence Airport). These extremely encouraging results will be presented and discussed. The performance of our system will be assessed, the main issues discussed and finally a comparison between a theoretical error model and the experimental result will be made. We will then conclude on the perspectives of our work, especially on the short-term and middle term ameliorations we hope to make within the project, and also leads for further work.

8439-27, Session 4

Night vision imaging systems integration into the Italian TORNADO IDS and ECR aircraft

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This paper describes the developmental and testing activities conducted by the Italian Air Force Official Test Centre (RSV) in order to confer the Night Vision Goggles (NVG) capability to the Italian TORNADO IDS (Interdiction and Strike) and ECR (Electronic Combat and Reconnaissance) aircraft. The activities included various ground sessions and a total of eighteen flight test sorties. RSV and Litton Precision Products were responsible of coordinating and conducting the installation activities of the internal and external lights. Particularly, an iterative process was established, allowing an in-site rapid correction of the major deficiencies encountered during the ground and flight test sessions. Both single-ship (day/night) and formation (night) flights were performed, shared between the Test Crews involved in the activities, allowing for a redundant examination of the various test items by all participants. An innovative test matrix was implemented by RSV for assessing the operational suitability and effectiveness of the various modifications implemented. Also important was definition of test criteria for Pilot and Weapon Systems Officer (WSO) workload assessment during the accomplishment of various operational tasks during NVG missions. Furthermore, the specific technical and operational elements required for evaluating the modified helmets were identified, allowing an exhaustive comparative evaluation of the two proposed solutions (i.e., HGU-55P and HGU-55G modified helmets).

The results of the activities were very satisfactory. The initial compatibility problems encountered were progressively mitigated by incorporating modifications both in the front and rear cockpits at the various stages of the test campaign. This process allowed a considerable enhancement of the TORNADO night vision systems configuration, giving a good medium-high level NVG operational capability to the aircraft.

Further developments currently ongoing in Italy, include the internal/external lighting for the Italian TORNADO "Mid Life Update" (MLU) and other programs, such as the AM-X aircraft internal/external lights modification/testing and the activities addressing low-altitude NVG operations with fast jets (e.g., TORNADO, AM-X, MB-339CD), a major issue being the safe ejection of aircrew with NVG and NVG modified helmets. Two options have been identified for solving this problem: modification of the current Gentex HGU-55 helmets and design of a new helmet incorporating a reliable NVG connection/disconnection device (i.e., a mechanical system fully integrated in the helmet frame), with embedded automatic disconnection capability in case of ejection. Other relevant issues to be accounted for in these new developments are the helmet dimensions and weight, the NVG usable FOV as a function of eye-relief distance, and helmet centre of gravity (moment arms) with and without NVG (impact on aircrew fatigue during training and real operational missions).

8439-28, Session 5

Nanophotonic sensors

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Device structures such as photonic crystals, photonic wires and optical metamaterials - all with submicron features can be described as 'nanophotonic'. Many of these devices and structures can be used

as sensors - relying on the change in refractive index of a surrounding medium. In this paper, we discuss several nanophotonic sensing systems, including asymmetric split ring resonators, photonic wire cavities and polymer Bragg gratings. In particular we consider the relative merits of high Q structures with a small shift in wavelength from the analyte versus low Q structures with a large shift in wavelength.

8439-29, Session 5

Whispering gallery mode pressure sensing

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Optical resonances of microresonators, also known as whispering gallery modes, are attracting considerable interest as highly sensitive measuring devices with a variety of applications. Such resonators can be used for pressure, force or strain measurement. Droplets, embedded in an appropriate substrate, form perfect spheres due to their surface tension and can be used as optical resonators with high quality factors. The resonance frequencies of these droplets depend sensitively on their size. Pressure changes affect the droplet size. Therefore, pressure change can be measured with high sensitivity. In the work presented here, Ethanol droplets in a size range between 80 and 100 µm embedded in a silicone matrix are considered. The resonance shift of the incident light with respect of the applied pressure is investigated. Since resonances at the laser wavelength are not visible directly, fluorescent dye is used to enhance the contrast between resonance and off-resonance case.

8439-30, Session 5

Cavity optomechanical magnetometer

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Here we demonstrate for the first time a cavity optomechanical magnetometer where the magnetic field induced expansion of a magnetostrictive material is transduced onto the physical structure of a highly compliant optical microresonator. The resulting motion is read out optically with ultra-high sensitivity. According to our theoretical model sensitivities of up to 500 fT per root Hz may be possible. The simultaneous presence of high-quality mechanical and optical resonances in optomechanical systems greatly enhances both the response to the magnetic field and the measurement sensitivity.

As a first proof of principal demonstration of an optomechanical magnetometer, we attached a piece of the magnetostrictive material Terfenol-D to the top of a toroidal whispering gallery mode resonator that had an outer diameter of 0.06 mm. Two 20 mm diameter coils generated a sinusoidal modulated magnetic field that induced periodic deformations of the magnetostrictive material and excited mechanical vibrations. By coupling light from a laser to the resonator close to the wavelength of an optical resonance, the mechanical vibrations were imprinted on the transmission spectrum and could be detected all optically. We achieved a peak sensitivity of 400nT per root Hz. Improving the mechanical coupling of the Terfenol-D to the resonator should significantly enhance the sensitivity according to our theoretical model. This may be achieved by sputter deposition of Terfenol-D onto the resonator.

Optomechanical magnetometers combine high-sensitivity, large dynamic range with small size and room temperature operation, and provide an alternative to atomic magnetometers which are relatively large in size and have a low dynamic range. This new type of sensor offers a non-cryogenic alternative to SQUIDs and may enable the construction of cryogenic free, low-field NMR and magnetic resonance imaging systems and high-density magnetometer arrays for magnetic field mapping.

8439-31, Session 5

Design, fabrication and measurements with a UV linear-variable optical filter microspectrometer

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Low-cost single-chip spectrometers have huge potential in systems for biomolecule identification and chemical analysis by optical absorption, fluorescence and emission line characterization. Such microspectrometers offer significant advantages over existing instruments, including size reduction, small sample size, low cost, fast data-acquisition and high reliability. UV spectroscopy has many potential application in pharmaceutical analysis, quantitative analysis of transition metals and bimolecular identifications. MEMS-based microspectrometers operating in the UV spectral range require either small feature size in grating design or a cavity width less than 140 nm in optical resonator design. Fabrication and electronic modulation of a resonator with such a narrow airgap between the two mirrors is severely hindered by capillary forces inside of the cavity. Also, electrostatic pull-in and subsequent sticking of the two mirrors limits the operating range of the device. These problems are avoided in solid-state UV optical filters fabricated in post-processing steps after completion of UV detector and circuit in a standard technology. The LVOF is based on a tapered cavity on top of a linear array of photodetectors. This paper presents the design, fabrication and spectral measurements of an Ultra-Violet (UV) Linear Variable Optical Filter (LVOF)-based micro-spectrometer operating in the 300 nm - 400 nm wavelength range. The UV LVOF has been fabricated in an IC-Compatible process using resist reflow. Characterization of the LVOF, by passing monochromatic light through the LVOF, shows high linearity of the profile. The filter provides the possibility to have a robust high-resolution micro-spectrometer in the UV on a CMOS chip. Spectrum of a Mercury lamp has been measured using the UV LVOF-microspectrometer with 0.5 nm spectral resolution.

The designed thicknesses for the multilayered LVOF are presented. HfO2 and SiO2 have been used as high-n and low-n materials. The thickness of the tapered cavity layer changes linearly from 440 nm to 600 nm. Fabrication has been done in an IC-Compatible process. a photograph of a fabricated UV LVOF is given. the image recorded by the CMOS camera at different wavelengths is shown. We can note the movement of illuminated regions on the camera for each wavelength shift. The illuminated region shift around 5 pixels for each 1 nm of wavelength shift. the image recorded on the camera when it is illuminated by Mercury lamp through the UV LVOF is shown. Signal processing has been used on the image to calculate the spectrum. The calculation result is compared with the spectrum as measured by monochromator and comments are given regarding the spectral resolution. It is expected to achieve 0.5 nm spectral resolution and the limitation comes from the current calbration method.

8439-32, Session 5

Roughness sensor based on a compact optoelectronic emitter-receiver modules

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In construction and manufacturing the surface roughness and their control plays a major role. The mechanical test probes are used in many application, because the advantage of the higher resolution of optical systems often plays no role. But in all cases the measurement systems were uses outside of fabrication processes due to the complex and expensive equipment. To overcome these we developed an roughness sensor suitable for an auto-mated control of machined surfaces. The sensor is able to handle high throughput and parallel systems is due to the low cost available. Our solution is a compact stand-alone sensors that can be simple integrated in existing systems like machine tools or transport systems. The sensor is based on a diode laser, focussing

optics and a special silicon photo diode array in an stable housing. The Single-mode VCSEL at 670 nm emission wavelength is focused on the surface of the sample at distance of 5mm. The light was reflected from the test surface and detected with an 8-channel photodiode array. The position of the main reflex allows an optimisation of the sensor distance to the surface. During the movement of the sample with a known velocity roughness depended signals over time were recorded at 8 cannels. This allows an detection of the angular distribution of the scattered light in combination of position dependent refection. It was shown here that we be able to achieve resolution below the spot diameter (10µm FWHM). We verify the sensor capabilities for real world applications on drilled samples with typical roughness variations in micro meter range.

8439-33, Session 5

Polarization effects in epoxy channel waveguides fabricated for sensing applications using UV lithography

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We present transmission characteristics of epoxy channel waveguides operating in single mode regime that can be potentially used as effective sensing platform. The investigated waveguides of different widths were fabricated using conventional i-line UV lithography technique at 365nm in a specially mixed polymer based on SU8 oligomer as a host and low refractive index monomer as a guest. A few-step fabrication process was adapted for standard 4" wafer size. A special focus was on polarization effects induced by material shrinkage during the fabrication process. We first conducted the systematic AFM measurements of topography of the top waveguides surfaces, which show much greater material shrinkage in the core region than in the cladding. We also measured the shrinkage-induced retardation distributions across the waveguides in transverse illumination. In the next step, we studied the impact of material shrinkage of transmission characteristics of the fabricated waveguides. We show that phase modal birefringence exceeds 10-3 in the short wavelength range and strongly decreases at longer wavelengths. The group modal birefringence measured using spectral interferometry method is in the range 0.6 - 1.4×10-3 depending on the waveguide width and shows little spectral dependence. For the waveguides of greater width, we detected significant polarization dependent loss caused by the leakage of the mode with electric vector perpendicular to the guiding layer. Small polarization cross talk between the fundamental mode and the cladding modes was also observed. Finally, we demonstrate the integrated Mach-Zehnder interferometer fabricated using developed technology.

8439-34, Session 5

Fluorescence-based optochemical sensor on flexible foils

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This paper describes the implementation of a low-cost technology platform for fluorescence-based optochemical sensors made up of arrays of multimode lightguides and coupling structures integrated onto a flexible substrate. Such a configuration is ideal for multi-analyte detection owing to a possibility of future integration of light sources, presence of fluorescent sensing elements, and photodetectors [1]. This optochemical sensor has wide-range of applications in medical, biochemical, and environmental diagnostics.

Flexible lightguides fabricated using two technologies, photolithography in the case of silsesquioxane-based polymers (LightLinkTM) and soft-lithography based replication techniques followed by capillary filling in the case of poly(dimethylsiloxane) (PDMS), are used in combination with 45° micromirror coupling structures, having a loss of 0.5dB. Fluorescent dyes are incorporated with the lightguides enabling a detection of shift in fluorescence-peaks in contact with gases, which are read-out at the detection arm in combination with filters.

Spectral transmission characteristics for several wavelengths from visible to mid-IR are obtained for polymer-foils and are compared with loss values obtained by cut-back measurements of lightguides. A propagation loss smaller than 0.24dB/cm was found. Refractive index measurements were performed using an ellipsometric technique and coupling elements were designed based on these values. Auto-fluorescence curves are also analysed to select the appropriate polymers for specific applications. Initial fluorescence-shift measurements yielded promising results enabling multi-analyte detection.

[1] Ultrathin optoelectronic device packaging in flexible carriers. Erwin Bosman, Jeroen Missinne, Bram Van Hoe, Geert Van Steenberge, Sandeep Kalathimekkad, Jurgen Van Erps, Ivaylo Milenkov, Krassimir Panajotov, Tim Van Gijseghem, Peter Dubruel, Hugo Thienpont and Peter Van Daele. IEEE Journal of Selected Topics in Quantum Electronics. Vol. 17. 2011. 617-628.

8439-35, Session 5

Micromirror-based sending and detection optical assembly for time-of-flight laser scanners

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We design an optical head for an imaging depth scanning device. In combination with fast (1 MHz pixel rate) laser time-of-flight distance measurement the optical head is intended for use in 3D cameras, enabling video frame rates (224 x 168 pixel at 24 Hz, selectable) and online selection of regions of interest.

Challenges are (i) to permit light collection from close-up surfaces,(ii) maximize optical efficiency for large distances, (iii) to reduce the dynamical range of signal returns and (iv) to minimize parasitic scattering.

We present a solution based on coaxial beam guidance, where the emitted beam first passes a beam splitter, is then deflected by a dedicated emission mirror in the center of a point-symmetrical, synchronized arrangement of 5 elliptical (3.6 mm x 2.6 mm) micro mirrors and finally passes a protective spherical glass cover. The mirror is slightly displaced from the center of the dome in order to collect parasitic reflections from the cover in a secondary focus. The light scattered at the target surface reaching the mirror array is directed towards an assembly of rhomboid prisms. These prisms reshape the distributed mirror array aperture such that a 12 mm diameter aspherical lens with a numerical aperture of 1.2 suffices to focus the light onto a fast, small-area avalanche photodiode. Advantageous properties of our approach are (i) no reduction of signal power by aberration, (ii) increased detector angle of field and (iii) vignetting of stray light.

8439-36, Session 5

Selectivity of spatial filtering velocimetry of objective speckles for measuring out-of-plane motion

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We probe the dynamics of objective laser speckles as the distance between the object and the observation plane continuously changes. With the purpose of measuring out-of-plane motion in real time, we apply optical spatial filtering velocimetry to the speckle dynamics. To

achieve this, a rotationally symmetric spatial filter is designed. The spatial filter converts the speckle dynamics into a photocurrent with a quasi-sinusoidal response to the out-of-plane motion. Our contribution presents the technology and discusses the selectivity of the spatial filter. Specifically, we discuss how we compromise the selectivity of the spatial filter with regard to radial speckle motion in order to gain tolerance towards in-plane speckle motion. The spatial filter is emulated with a CCD camera, and is tested on speckle acquisitions obtained from a controlled set-up. Experiments with the emulated filters illustrate performance and potential applications of the technology.

Measurements of long range axial displacements (23 mm) are obtained giving a random error of +/-0.5 mm. Measurements of short range axial vibrations are obtained with a noise-equivalent power corresponding to amplitudes of 0.001 mm.

8439-37, Session 6

Detection limits in whispering gallery mode biosensors with plasmonic enhancement

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We perform numerical modeling of a gold nanorod bound to the surface of a microtoroid-based WGM biosensor.

Localized surface plasmon resonances in the nanorod give rise to strong enhancements in the electric field when excited near resonance, increasing the frequency shift for a single BSA molecule by a factor of 870, with even larger enhancements predicted for smaller proteins. On resonance, the frequency shift is predicted to be on the order of MHz, several orders of magnitude larger than measurement noise arising from time-averaged frequency and thermal fluctuations.

Whispering gallery mode (WGM) resonators such as silica microspheres and microtoroids have unprecedented sensitivity as biological sensors due to their small optical mode volume and ultra-high quality factor (Q > 10^8) in water. The interaction between the resonator's evanescent field and a molecule that binds to the resonator's surface induces a resonance frequency shift. This shift is proportional to the polarisability of the molecule and the square of the electric field at the position of the molecule. By attaching metallic nanoparticles with plasmon resonances to the surface of the microtoroid the local electric field can be enhanced, significantly increasing the frequency shift induced by a molecule.

We performed numerical modelling of a gold nanorod bound to the surface of a microtoroid-based WGM biosensor using the boundary element method (BEM). Localized surface plasmon resonances in the nanorod give rise to strong enhancements in the electric field when excited near resonance, increasing the frequency shift for a single BSA molecule by a factor of 870, with even larger enhancements predicted for smaller proteins. On resonance, the frequency shift is predicted to be on the order of MHz, several orders of magnitude larger than measurement noise arising from time-averaged frequency, phase and thermal fluctuations. We found that under typical experimental conditions the minimum detectable polarizability of a bound molecule is reduced to about 10 Angstrom^3. This is well below the limit required to measure both single molecule binding events as well as conformational dynamics in some proteins.

8439-38, Session 6

Molecular detection via quasi-phase matched second harmonic in the whispering gallery modes

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Spherical microresonators have been demonstrated to be potential label-free tools for identifying chemical species on the sub-nanoscale level. Here a novel sensor based on the high Q spherical microresonators will be presented. Recently, it was demonstrated that WGM spherical microresonators provide surface second harmonic light generation from a low number of small molecules [1]. The sensor signal is in this case directly related to the chemical distribution found at the surface. Results will be presented for the proof of principle of a new device integrated by an inert material onto which a periodic patterning is lithographically imprinted allowing the WGM generation of the second harmonic of only those analyte molecules attached to the imprinted area. The realistic implementation of the device will be discussed, as well as its prospective capabilities for bio- and chemical sensing for large and small molecules.

[1] J. L. Domínguez-Juárez, G. Kozyreff, J. Martorell, Whispering gallery microresonators for second harmonic light generation from a low number of small molecules, Nature Commun. 2, 254 (2011)

8439-39, Session 6

Protein detection system based on 32x32 SPAD pixel array

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In this work, a compact low-cost system designed to detect traces of proteins in biological fluids is presented. The system, based on time-gated fluorescence detection principle, is composed by a Single-Photon Avalanche Diode (SPAD) image sensor, an excitation light source and a micro-machined reaction chamber coupled to a microfluidic network. Fluorescence light from the detection sites is collected through a high numerical aperture objective and filtered through an interference band-pass filter.

The sensor is based on a 32x32 CMOS pixel array, having 25µm pixel pitch and 20.8% fill factor. Each pixel is composed of a SPAD and a time-gated analog counter, and is capable of nanosecond gating at up to 80MHz pulse repetition rate. The compact in-pixel analog counter transforms the SPAD digital pulses occurring inside a gating window to a small charge pulse discharging an accumulation capacitance. In this way, the capacitance voltage is proportional to the number of SPAD counts and the pixel can be read out using conventional CMOS image sensor readout circuits. If the capacitance discharge voltage corresponding to a single photon detection is much larger than the readout noise, the imager noise is determined by the shot noise of light and dark counts, while electronic readout noise is negligible.

A pulsed LED is used as fluorescence excitation source. LED light is focused and filtered in order to reduce its spectral bandwidth. Pulsed operation is used together with sensor gating to reduce the effect of detector dark counts on the measurement precision, while allowing the use of a small average excitation power.

The reaction chamber is based on an array of micro-wells fabricated on a silicon substrate, closed with an optically transparent thick membrane (2µm) made of a $SiO_2/Si_3N_4/SiO_2$ multilayer. The reaction chamber top and side-walls as well as the fluidic layer, are realized in molded PDMS.

Each micro-well, corresponding to a reaction site, could be individually functionalized with DNA aptamers, able to immobilize specific proteins. A fluorescent labeled aptamer is used to target the trapped protein at a secondary binding site. The detection of the human thrombin protein is reported as a biological proof of principle of the biosensor.

8439-40, Session 6

Differentiation of microstructures of sugar foams by means of spatially resolved spectroscopy

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Food microstructure is defined as the organization of food constituents at the microscale and their interaction. Most solid foods, including bakery and confectionary products, fruits, vegetables and meat, are microstructured. Many properties of foods that are relevant to food process engineering or quality are related to their microstructure. Examples include sponginess of bread, crispiness or crunchiness of crackers, gas and water transport properties of fruit, and color as related to light scattering properties just beneath the surface of the food. Food processing operations affect the food microstructure: existing structures are destroyed and new ones are created. Insight in the food microstructure and how it changes during processing operations are essential to produce high quality food. In particular, consumer demands for enhanced nutritional quality, sensory quality and safety are driving manufacturers to optimize products and processes with respect to microstructure.

Until recently, the measurement of food microstructure was essentially based on light or electron microscopy. Because of the often considerable sample preparation time, cost and complexity of the equipment, such techniques were mainly used for academic purposes, but seldom in a food industrial environment. Thanks to recent advances in spectroscopic techniques and photonics devices, non-destructive assessment of the food microstructure now becomes possible. As the interaction of propagating light with food matrices is dominated by scattering, related to refractive index differences and thus the microstructure, and absorption, related to the chemical composition, separation of these two phenomena in the post-interacting light would provide information on the food microstructure and composition.

Separation of the scattering and absorption properties of biological tissues has been demonstrated in the biomedical domain by combining multiple spectroscopic measurements resolved in space or time with light propagation models. While successful results have been reported for both time and spatially resolved spectroscopy, the equipment for the latter is much more cost-effective and better suitable for use in the food industry. Therefore, spatially resolved spectroscopy was used in this study.

A setup for spatially resolved spectroscopy was elaborated by combining a fiber-optics probe with a spectrograph-camera combination for measurement in the 400-1000 nm range. The probe consists of seven optical fibers: one serves as illumination fiber and the others serve as detection fibers to collect diffuse reflected light at different source-detector distances ranging from 0.3 to 1.2 mm.

This probe has been used to characterize sugar foams prepared under different processing conditions (foaming times) to create different air bubble size distributions in them. These different microstructures were expected to produce different scattering properties of light thanks to the mismatch in refractive indices at the bubble interfaces. Preliminary results have shown significantly different reduced scattering coefficients in the range 400-1000 nm of 3 sugar foams prepared with foaming times of 1, 5, and 10 minutes; which indicated that different bubble size distributions in these foams, or different microstructures, have been successfully differentiated non-destructively by spatially resolved spectroscopy technique.

The successfulness of this research would provide a non-destructive and valuable method for assessing microstructure-related qualities and process control of many foods with an air phase: confectionary products, marshmallow, pulled sugar, nougat and even chocolate...

8439-41, Session 6

Hybrid spectroscopic instrument for in-line nanoparticle detection and characterization

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The field of nanotechnology is currently experiencing a stage of exponential growth. Nanoparticles (NP) enter our daily lives through a range of consumer goods. Currently over 1000 consumer products contain NPs such as cosmetics, sunscreens, paints and surface coatings. One essential prerequisite for the development, manufacturing and commercialization of NPs is the availability of techniques and tools for real time characterization at the nanoscale level. There is a considerable arsenal of detection and characterization methods for nanoparticles available, however, all of them are laboratory based equipment and not used for in-line monitoring. The major drawback with these instruments is their large size and the lack of smart software and integration modules to apply them in-line.

Here, we use Raman spectroscopy combined with Laser Induced Breakdown Spectroscopy (LIBS) to fully characterize the NP chemical composition and determine their size with a detection limit of a few nanometers.

Raman spectroscopy is an inelastic light-scattering technique which provides the vibrational frequencies associated with the NP molecular bonds or breathing modes. LIBS is based on the analysis of spectral emission from the nanoparticles in the plasma produced by the laser-induced breakdown.

In order to combine both techniques for in-line NP monitoring, we developed a novel Raman-LIBS setup that allows NP detection in liquids. We will also present measurements on carbon nanotubes using the same setup. Our results show that a large variety of NP can be detected, with dimensions ranging from 5 nm to a few micrometers, and at a wide range of concentrations within a few seconds. We are able to determine their chemical composition, doping concentration and core-shell ratio, as well as the particle size. Our method can now be applied for in-line NP detection during particle synthesis.

8439-42, Session 6

Functionalised planar Bragg grating sensor for the detection of BTX in solvent vapour

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We report on an optical planar Bragg grating (PBG) sensor functionalized by a simple method against substances such as benzene, toluene and xylene (BTX) in solvent vapour. BTX are among the group of volatile aromatic hydrocarbons occurring chiefly as a result of incomplete combustion of wood and fossil fuels. In particular, benzene was formerly used in industry, until it was superseded by its methyl substitutions toluene and xylene due to its characteristic of being both acute and chronic health hazard. Although benzene has been banned from most applications it is still used in pesticides in order to increase their solubility. [1-4]

The PBG sensor consists of three silica layers upon a silicon wafer. Both, the optical waveguide and the Bragg grating are generated in the germanium doped core layer by direct writing technique [5,6]. To facilitate evanescent field interaction of the guided mode a subsequent hydrofluoric etching step opens a sensing window by partly removing the upper cladding layer. In this respect, the PBG sensor represents a refractive index sensor.

To functionalise the sensor against BTX, substituted cyclodextrins were applied to the sensor surface using dip coating. These cyclodextrins have a relatively hydrophobic cavity which favours the accommodation of an organic molecule of appropriate dimensions leading to a non-covalent inclusion complex. The functionalized sensor was exposed to a stepwise increasing analyte enriched nitrogen stream leading to a quasi instantaneous spectral shift of the Bragg wavelength $\Delta\lambda_B$. The temporal evolution of λ_B reveals an exponential behaviour towards an equilibrium state for both rising and decreasing BTX exposure. The overall shift of λ_B shows a linear relationship to the analyte concentration. Taking into account the spectral resolution of the interrogation system we find minimum detectable concentrations of about 34 ppm for benzene, 12 ppm for toluene and 3 ppm for m-xylene, respectively.

REFERENCES

1. K. Demirbas and A. Sahin-Demirbas, "Gasoline Fuel Blends for Otto Engines and Gasoline Fuel Additives," Energy Sources, Part B: Economics, Planning and Policy 5, pp. 243-249, 2010.

2. M. Smith, "Advances in understanding benzene health effects and susceptibility," Annual review of public health 31, pp. 133-148, 2010.

3. T. Zhang, J. Huang, S. Deng, and G. Yu, "Influence of pesticides contamination on the emission of PCDD/PCDF to the land from open burning of corn straws," Environmental Pollution 159, pp. 1744-1748, 2011.

4. American Heritage Dictionary, The American heritage science dictionary, vol. 1st. Edition, Houghton Mifflin Company, 2005.

5. G. Emmerson, S. Watts, C. Gawith, V. Albanis, M. Ibsen, R. Williams, and P. Smith, "Fabrication of directly UV-written channel waveguides with simultaneously defined integral Bragg gratings," Electronics Letters 38(24), pp. 1531-1532, 2002.

6. I. Sparrow, P. Smith, G. Emmerson, S. Watts, and C. Riziotis, "Planar Bragg Grating Sensors-Fabrication and Applications: A Review," Journal of Sensors 2009, pp. 1-12, 2009.

8439-43, Session 6

Absolute refractive index and thickness measurement of ultrathin films in liquid environments with Bloch surface waves

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Optical biosensing relying on surface effects has become a popular detection principle to highlight specific molecular interactions [1]. Various functionalization methods to control the affinity of the surface to specific ligands by chemically active layers have been developed. The uniformity of these layers and of the subsequent interactions are key points for the quantitative analysis of the detected interactions. One of the main issues of most popular methods is to gain access to enough meaningful information to extract the quantities of interest in the presence of non-uniform binding at the surface [3].

Amongst the optical surface sensing schemes, Bloch surface wave (BSW) sensing has recently arisen revived interest [4,5]. BSW sensing is based on surface electromagnetic waves on top of dielectric multilayer (ML) structures. The resonance properties of these waves depend on the design of the ML stack, providing unprecedented versatility.

In this paper, we present a new measurement scheme, based on the BSW concept, providing, in one single self-referenced measurement, the determination of the bulk fluid refractive index, the adsorbed layer effective refractive index and its thickness. The method relies on monitoring at the same time up to five resonances of a specifically designed ML structure. We demonstrate experimentally the validity of the method by measuring polyethylene glycol (PEG) monolayers of different lengths and densities in saline solutions of variable concentrations. These results highlight the interest of BSW sensing as a tool for the quantitative analysis of surface interactions in biological environments.

[1] X. Fan, I. M. White, S. I. Shopova, H. Zhu, J. D. Suter, and Y. Sun, "Sensitive optical biosensors for unlabelled targets: A review", Anal. Chim. Acta 14 (2008), pp. 8-26

[2] P. Wu, D. G. Castner, and D. W. Grainger, "Diagnostic devices as biomaterials: a review of nucleic acid and protein microarray surface performance issues", J. Biomater. Sci. Polymer Edn 19 (2008), pp. 725-753

[3] S. Scarano, M. Mascini, A. P. F. Turner, and M. Minunni, "Surface plasmon resonance imaging for affinity-based biosensors", Biosen. Bioel. 25 (2010), pp. 957-966

[4] M. Shinn and W. M. Robertson, "Surface plasmon-like sensor based on surface electromagnetic waves in a photonic band-gap material", Sens. Act. B 105 (2005), pp. 360-364

[5] V. Paeder, V. Musi, L. Hvozdara, S. Herminjard, and H. P. Herzig, "Detection of protein aggregation with a Bloch surface wave based sensor", Sens. Act. B 157 (2011), pp. 260-264

8439-44, Session 6

Normal incident detection of chemical bonds at infrared wavelengths through extraordinary optical transmission of metallic membranes

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Infrared Spectroscopy is the most commonly used method of identifying the surface species generated by molecular adsorption and the species generated by surface reactions. Infrared spectroscopy is almost invariably done at non-normal incidence to increase detection sensitivity. However extraordinary optical transmission results in enhanced fields at the surface which allows chemical sensing at mid-IR wavelengths at normal incidence (2, 3). In this paper we show that extraordinary optical transmission can be used to make a sensor for industrial application which is more compact, easier to use, and has a narrow detection range to detect a specific IR absorption bands.

The detection surface is based on a free standing metallic membranes made by batch photolithography. The membrane consists of a 500nm thick silicon nitride layer with a square lattice of holes etched through it. Gold is sputtered to cover both sides of the membrane and inside the holes. These membrane surfaces show enhanced optical transmission at infrared wavelengths with excellent agreement between theory and experiment, see figure. The transmission measurements were made in a Bruker Vertex 70 FTIR. The modelling was made using the modal expansion model (4, 5).

We investigated how the transmission spectra depend on different parameters, such as membrane thicknesses, fill factors and periods. From this information a specific membrane was made to detect the absorption of the amide bond in the wavelength range of 1550-1700 cm-1. The detection of the amide bond is of interest for biological applications (protein peptide bond) and material science (amidic groups in smart polymers). This membrane made it possible to detect at normal incidence the chemical bond signature of the typical amide I and amide II absorption bands in the IR. In doing this we have created a simplified detection system with enhanced optical transmission at targeted wavelengths, which can be used as a chemical specific sensor.

1) T. W. Ebbesen, et al, 391 6679 1998

2) J. V. Coe et al, Annu. Rev. Phys. Chem. 59, 179-202, 2008

3) A. G. Brolo et al, Langmuir 20, 4813-4815 2004

4) L. Martin-Moreno et al. Journal of Physics, Condensed Matter 20, 2008

5) F. de León-Pérez et al. , New. J. Phys 10, 105017 2008

8439-45, Session 6

A low-cost optically efficient carbon dioxide sensor based on nondispersive infrared (NDIR) measurement at 4.2 µm

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Carbon dioxide measurements are required in many industrial applications including safety, combustion monitoring, indoor air quality and process control. Non-dispersive infra-red (NDIR) techniques have found great commercial importance in these applications, which can be sensitive to price, power consumption and the physical size of the sensor, especially for use in portable instruments. The so-called "pellistor format" sensor has become a default standard, consisting of

a cylinder with external dimensions 20mm diameter and 16mm length. Designs are typically built around a broadband incandescent source and an integrated package containing bandpass filters centred on 4.2μm (the CO_2 absorption band) and 3.95μm (a non-absorbed reference wavelength), each located above a separate matched detector element. The challenge is to fit the detector package (9mm diameter) and bulb (3mm diameter) within the internal diameter of the housing (17mm) with an optical pathlength sufficiently long for CO_2 detection at the tens of ppm level.

We present a new CO_2 sensor in this format. A compound parabolic concentrator collects light from a microbulb, and further parabolic mirrors deliver light to the two detector elements while maintaining a high étendue along the optical path. A semi-focused design, and a spherical mirror behind the bulb, accommodate manufacturing tolerances on the components, in particular on the position of the bulb filament. The reflective cell was designed using a commercial raytracing package and implemented in injection moulded thermoplastic, coated with gold. Compared to previous sensor designs, the signal to noise ratio is significantly improved. With an estimated optical pathlength of 32mm, detection of CO_2 has been demonstrated with a zero repeatability of ±10ppm (1σ). Alternatively, the design enables lower power operation of the microbulb and / or the use of lower cost detectors that have a lower detectivity (D*) and therefore higher noise equivalent power.

This paper will provide a detailed overview of the design principles and manufacturing technique used. If an oral presentation is proposed, it will be possible to provide moveable projections of 3-d models to illustrate the design and manufacturing process. Results will be presented showing sensor performance in a range of conditions.

8439-46, Session 6

Data-driven models for predicting the flame spectral behaviour in industrial combustion processes

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Flame spectroscopy is extensively used in the analysis of industrial combustion processes. Flame emits energy over a wide spectral region and their associated spectra contain continuous and discontinuous components. The continuous component is observed in the sooty region of the flame, while the discontinuous component is associated to free-radicals observed in the reaction zone. In the literature there are physical models, based on either Planck's or Wien's law, for representing the spectral behaviour of the process. However, the non-linear nature of these models, the high dimension of the spectral data, and the fact that the discontinuous radiation is superimposed over the continuous spectral emission makes the analysis of combustion process, by means of these theoretical models, a complex task.

In this paper exploratory data analysis is used to derive data-driven models for predicting the spectral behaviour of a flame combustion process. To do so, a database of measured spectra, collected from a real flame process in the range of 340 to 1025 nm, is used as a priori information about the process. The database contains spectral information about both, continuous and discontinuous emissions of natural gas, oil, and bio-oil fuels at different combustion conditions. To summarize in a reduced number of terms the whole spectral information contained in the database, standard as well as probabilistic principal components analysis are used to create linear data-driven predictive models for the combustion process. In addition, a non-linear model is also constructed from the data. The predicting performance of the models is tested using the goodness-of-fit and the root-mean-squared error. The applicability of the models is finally tested by devising a simple automated solution for separating the discontinuous radiation from the continuous emission.

8439-47, Session 6

Fluorescence spectroscopy: a promising tool for gear-oil condition monitoring

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Wind power is one of the most promising green energy sources, especially when produced in offshore power plants. Corrective operations in wind turbines cause a considerable part of the maintenance costs of such plants. One preventive action for reducing such operations is the periodic offline control of oil samples from the wind turbines. The time delay between sampling an availability of the results is a major disadvantage of this kind of controlling. In-situ condition monitoring is a solution to this problem. In-situ monitoring allows real time detection of random, time discrete events, thus enabling a better scheduling of preventive actions and reducing costs and downtime.

Fluorescence spectroscopy is a complementary technique to absorption spectroscopy. Due to absorption of UV or visible light, the electrons of certain compounds' molecules are excited from a ground electronic state to a vibrational state of higher energy. By collision with other molecules, the excited electron looses a part of the acquired energy and relaxes to a lower vibrational state. The remaining acquired energy is emitted during the electron's transition to the ground state. The resulting frequency shift between excitation and emission energy, known as Stokes Shift, is unique and characteristic for each active molecule.

In this paper gear-oil condition monitoring based on fluorescence spectroscopy is proposed. Three typical commercial gear-oils for wind turbines were studied. The spectra gained by UV-Excitation of the samples were analyzed by means of Partial Least Square Regression. Good prediction results were obtained for the Total Acid Number. The latter is a measure for the oil acidity and is considered to be a proxy variable for oil age. Other parameters delivering information about gear-oil additive depletion and the related oil aging condition, like phosphor, sulfur and molybdenum concentration, were also analyzed.

8439-48, Session 7

Trends in (CMOS) image sensors

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No abstract available

8439-49, Session 7

A novel JFET readout structure applicable for pinned and lateral drift-field photodiodes

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Enhancement of the dynamic range of photodetectors used in advanced image sensors such as time-of-flight sensors or image sensors for automotive applications is a major research topic. In this paper an improved unipolar readout structure is presented, that is superior to the widely employed source follower readout implemented by enhancement MOSFETs. It yields a high output voltage swing and low noise, while requiring no additional processing steps. The readout structure is consisting of a low-noise JFET whose gates are formed by a floating diffusion, thus preserving in-pixel accumulation capability - which additionally improves noise performance. This structure outperforms a simple in-pixel implementation of a JFET and a photodetector in terms of the necessary area consumption, thus improving fill factor. For pixels with a pitch of several microns this readout structure is a good trade-off between area, output voltage swing and, most important, noise performance. Furthermore, since only a ground connection is needed for application, fill-factor and power-grid disturbances like DC-voltage drop can be additionally improved.

8439-50, Session 7

A 64 single photon avalanche diode array in 0.18 µm CMOS standard technology with versatile quenching circuit for quick prototyping

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Several works have demonstrated the successfully integration of Single-photon avalanche photodiodes (SPADs) operating in Geiger mode in a standard CMOS circuit for the last 10 years. This devices offer an exceptional time resolution as well a very good optical sensitivity. Nevertheless, it is difficult to predict the expected performances of such a device. Indeed, for a similar structure of SPAD, some parameter values can differ by two orders of magnitude from a technology to another. We proposed here a procedure to identify in just one or two run the optimal structure of SPAD available for a given technology. A circuit with an array of 64 Single Photon Avalanche Diodes (SPAD) has been realized in the Tower-Jazz 0.18 µm CMOS image sensor process. It encompasses an array of 8 different structures of SPAD reproduced in 8 diameters in the range from 5 µm up to 40 µm. According to the SPAD structures, efficient shallow trench insulator and/or P-Well guard ring are used for preventing edge breakdown. Low dark count rate of about 100 Hz are expected thanks to the use of buried n-well layer and a high resistivity substrate. Each photodiode is embedded in a pixel which includes a versatile quenching circuitry and an analog output of its cathode voltage. The quenching system is configurable in four operation modes; the SPAD is disabled, the quenching is completely passive, the reset of the photodiode is active and the quenching is fully active. The architecture of the array allows the characterization of every single photodiode individually. The measured parameters for each photodiode are the breakdown avalanche voltage, the dark count rate, the dead time, the timing jitter, the photon detection probability and the after-pulsing rate. The test benches as well as the characterization methods for each parameter are detailed. The circuit will be tested on December, January and February; results will be available for the final submission.

8439-51, Session 7

Vulnerability of optical detection systems to megajoule class laser radiative environment

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The Laser MegaJoule (LMJ) facility will host inertial confinement fusion experiments in order to achieve ignition by imploding a Deuterium-Tritium filled microballoon. In this context an X-ray imaging system is necessary to diagnose the core size and the shape of the target in the 10-100 keV band. Such a diagnostic will be composed of two parts: an X-ray optical system and a detection assembly. Each element will be affected by the mixed pulse consisting of X-rays, gamma rays and 14 MeV neutrons created by fusion reactions.

The design of this diagnostic will take into account optics and detectors vulnerability up to a maximum neutron yield of 10^16. In this work, we will present the main results of our vulnerability studies and of our hardening-by-system and hardening-by-design studies.

One way to protect the diagnostic consists in recording image in a box shielded against the radiations. The X-ray image of the core will be formed on a scintillator through an X-ray optical system. Then, the visible light induced by the scintillator will be easily transferred through an optical relay to shielded box and focused on a detector.

Experimental studies and Monte-Carlo simulations are led to maximize the sensibility of each parts of the plasma diagnostic to X-ray core emission and to minimize their sensitivities to neutrons and gamma rays:

- Homemade scintillators are developed in order to adapt their effective atomic number, their decay time and their emission spectrum to the detection scheme.
- Various optical relay systems have been exposed to harsh environment and compared in terms of radiation hardness to identify the most promising scheme.
- The radiation sensitivities of CCD and CMOS image sensors during DT shots on OMEGA facility have been compared.

8439-52, Session 8

Novel pyroelectric infrared sensors for PIR motion detectors

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A PIR motion detector basically consists of a thermal infrared sensor, an infrared optics and a signal processing unit. Often multi-fresnel lenses are used as the optics and compensated pyroelectric dual-element sensors are used as the infrared sensor. The pyroelectric detector has typical two symmetrical elements with an area of [2x1] mm2 and a distance of 1 mm. The multi-fresnel lens projects different room segments onto the pyroelectric detector. If a heat source (person) moves in these room segments an electrical output signal is produced by the detector and processed by the evaluation unit. Commercially available PIR detectors can sense only the presence of moving objects in their surveillance area but they can't give information about the direction of movement.

The paper describes the layout and essential properties of novel dual-element detectors with an innovative layout of the pyroelectric chip. The pyroelectric material used is lithium tantalate. Geometry and arrangement of the responsive elements ensure different time depended signals for different movement directions. It is shown that the signal's time behavior correlates with the direction of movement. The paper describes also a complete PIR motion detector with the new dual-element detector and the measurement results.

8439-53, Session 8

PbTe(In) films with variable microstructure for photodetection in IR and terahertz range

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Lead telluride based semiconductors are commonly associated with optical sensing in the IR spectral region. Indium doping allows extending the photosensitivity up to the terahertz range. In the present work, we show that PbTe(In) films may be photosensitive up to the wavelength of 280 m. Depending on the film microstructure and the temperature range, the signal may be of a positive or negative sign, of persistent character or just following the laser pulse shape.

The work deals with studies of the grain size and surface state effect on photoelectric and transport properties of PbTe(In) films in the temperature range from 4.2 K up to 300 K, in DC and AC modes, under irradiation of a blackbody source and terahertz laser pulses.

The PbTe(In) films were deposited on insulating substrates kept at the temperatures TS equal to -120 Ñ è 250C. AFM, SEM, Auger spectroscopy and X-ray diffraction were used to study the film microstructure. Thickness of the films was varied within 0.1 - 1 µm. Increase of the TS value led to mean grain size growth from 60 up to 300 nm. All films had a column-like structure with the columns nearly

perpendicular to the substrate plane. In the polycrystalline films with the mean grain size of 300 nm, appearance of the (200) preferred orientation of the columns was observed.

It is shown that microstructure of the films strongly affects the photoconductivity character in the terahertz region of the spectrum. Positive persistent photoresponse is observed at low temperatures in the polycrystalline films. For these films transport and photoelectric properties are determined by the grain volume and impurity state specifics. Nanocrystalline films have all features of non-homogeneous systems with band modulation. For these films only negative photoconductivity is observed in the whole temperature range. Possible mechanisms of the photoresponse formation are discussed

8439-54, Session 8

Multispectral InAs/GaAs-based quantum dot infrared photodetector with quaternary (InAlGaAs) capping layer operates at low bias voltage

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In recent past Quantum dot (QD) infrared photodetector has drawn significant attention due their potential applications in the field of medical, defense and space research and technology. Exploiting the advantage of three dimensional confinement of the carriers inside the dots which provides intrinsic sensitivity to normal incident radiation and long excited state lifetime, different groups have contributed to the evolution of detector technology. Still it is a big challenge to reduce the dark current and achieve multi-spectral response from the device at low operating bias voltage in order to extend its limit of applications. In this contribution we have investigated the performance of InAs/GaAs based detector with quaternary InAlGaAs quaternary capping and report multi-spectral response from the detector over a broad range (5-10µm) at low bias voltage with reduced dark current. The sample was grown by solid source MBE and had three(3) stacks of ten(10) 2.7ML InAs QDs were grown with a combination capping of 20Å In0.21Al0.21Ga0.58As and 65Å GaAs. Three stacks were separated from each other by a 1000Å GaAs layer. Quaternary layer acts as a surface driven phase separation alloy producing defect-free QDs in the active region. XTEM images show the formation of strain coupled QDs in each stack and strong photoluminescence attests the high quality of the material. Spectral response measurement at 77K shows the existence of three spectral peaks at 5.5µm (MWIR) and 8.0µm and 9.5µm (LWIR) at 0.3V optimum bias voltage. The 9.5µm peak measures a peak detectivity of 1.6x10^9 cm Hz^1/2/W at 77K. Dark current measurement confirms significantly low dark current density (1.4x10^(-7A)/cm2 at applied bias of 2Vat 77K).
DST India is acknowledged.

8439-55, Session 8

Characterization of InSb QDs grown on InAs (100) substrate by MOCVD and MBE for infrared photodetectors

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Photodetection based on InSb is a well-known technology for mid wave infrared range (3-5 µm). A promising way of extending the detection wavelength into the long-wave infrared range is by incorporating InSb nanostructures in a suitable matrix [1]. The band alignment of InSb quantum dots (QD) in InAs matrix results in a strong confinement of holes in the InSb dot with quantized energy levels. Such a system offers spatially indirect transitions between the dot and the matrix material [2], which can be extended into the long wave range by changing the size and composition of the dots. However, in order to understand and develop the material system, structural and optical characterizations are crucial.

We report on the optical and structural characterization of InSb QDs in InAs matrix, grown on InAs (100) substrates, for infrared photodetectors. Samples with different thicknesses of InSb layers are grown by the techniques of MBE and MOVPE. Photoluminescence measurements reveal strong QD related peaks between 3.8 to 6.2 µm in the MOVPE grown structures, depending on the InSb layer thickness. This is the longest wavelength reported so far in this material system. Structures grown by MBE reveal QD related luminescence at 4 µm. AFM measurements of MBE grown structures show surface dots of ~ 35 nm in size and ~3 nm in height, with a density of about 2 x 10^10cm-2. Cross-section TEM investigations of buried InSb layers grown by MBE show coherently strained QDs for a nominal InSb thickness in the 1.6 - 2 ML range. Layers with InSb > 2ML contain relaxed QDs with structural defects due to large amount of strain between InSb and InAs. Samples with such large dots do not show any InSb related luminescence. Photodetector device structures containing multiple InSb QD layers have been grown and characterized.

[1] C.J. Hill, A. Soibel, S.A. Keo, J.M. Mumolo, D.Z. Ting and S.D. Gunapala ELECTRONICS LETTERS 2nd September 2010 Vol. 46 No. 18

[2] O. Gustafsson , J. Berggren, U. Ekenberg, A. Hallén, M. Hammar, L. Höglund, A. Karim, B. Noharet, Q. Wang, A. Gromov, S. Almqvist, A. Zhang, S. Junique, J.Y. Andersson, C. Asplund, R. Marcks von Würtemberg, H. Malm, H. Martijn, Infrared Physics and Technology, Infrared Physics & Technology 54 (2011) 287-291

8439-56, Session 8

Hybrid graphene-quantum dot phototransistors with ultra-high gain

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In recent years there have been many scientific efforts to explore the extraordinary properties of graphene for electronics, optics and material applications. Since its discovery in 2004, this new semiconductor with zero band gap, consisting of a single atomic layer of carbon atoms arranged in a hexagonal lattice, continues to exhibit surprising characteristics [1], including carrier mobilities of 60.000 cm2/Vs at room temperature [2], ultra-fast optical response time and broad spectral bandwidth [3]. Moreover, graphene's small size and ease of fabrication makes it a good candidate for integration into low power photo-detection architectures with CMOS technology, contrary to contemporary technologies, such as avalanche photo diodes and photomultipliers which are bulky and require the application of high biases. Here, we present a novel type of graphene-based photodetector, by combining the extraordinary properties of graphene with the optical properties of colloidal quantum dots, which include high absorption coefficients as well as band gap tunability by quantum confinement [4], to realize a novel photo-detection scheme based on a hybrid graphene-quantum-dot photo-transistor. Using this device we have achieved photo-conductive gain as high as 108 at room temperature while applying electric fields as low as 103 V/cm. This highly sensitive photodetector can detect power in the fW regime while covering a broad spectral bandwidth, from the visible to the near infrared, and its responsivity can be tuned by electrostatic gates.

[1] K. S. Novoselov et al., Science, 306, 666 (2004).

[2] C. Dean, A. Young, I. Meric, and C. Lee, Nature Nanotechnology 5, 722 (2010).

[3] F. Xia., T. Mueller., Y. M. Lin, A. Valdes-Garcia and P. Avouris, Nature Nanotechnology 4, 839 (2009).

[4] G. Konstantatos et al., Nature, 442, 180 (2006).

8440-01, Session 1

Quantum optomechanics: a mechanical platform for quantum foundations and quantum information processing

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Massive mechanical objects are now becoming available as new systems for quantum science. Quantum optics provides a powerful toolbox to generate, manipulate and detect quantum states of motion of such mechanical systems - from nanomechanical waveguides of some pictogram to macroscopic, kilogram-weight mirrors of gravitational wave detectors.

Recent experiments, including laser-cooling of massive mechanical devices into their quantum ground state of motion, and demonstrations of the strong coupling regime provide the primary building blocks for full quantum optical control of mechanics, i.e. quantum optomechanics. This has fascinating perspectives for both applications and for quantum foundations: For example, the on-chip integrability of nano- and micromechanics, together with their flexibility to couple to different physical systems, offers a novel perspective for solid-state quantum information processing architectures. At the same time, mechanical resonators provide access to a hitherto untested parameter regime of macroscopic quantum physics via the generation of superposition states of massive systems and of optomechanical quantum entanglement, which is at the heart of Schrödinger's cat paradox. Finally, due to the large mechanical mass, table-top quantum optomechanics experiments even allow to explore the fascinating interface between quantum physics and (quantum) gravity.

8440-02, Session 1

Probabilistic heralded phase-insensitive optical squeezer

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A non trace-preserving map describing a probabilistic but heralded noiseless linear amplifier has recently been proposed and experimentally demonstrated. Here, we exhibit another remarkable feature of this peculiar amplifier, namely its ability to serve as a single-mode squeezer regardless of the quadrature component that is initially squeezed. Hence, it acts as an heralded phase-insensitive optical squeezer, conserving the signal-to-noise ratio just as a phase-dependent optical amplifier but for all quadratures at the same time. This quantum optical effect may open new perspectives in quantum optical communications. Although this ability to squeeze all quadratures seemingly opens a way to instantaneous signaling following Diek's approach to the quantum no-cloning theorem, we show that the probability for such a causality violation vanishes.

8440-03, Session 1

Reconstruction of multiphoton Bell states using 3D quantum polarization tomography

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Macroscopic Bell states manifest multi-photon entanglement in two polarization and two frequency (or angular) modes of radiation. These non-classical states of light are particularly useful owing to their stronger interaction with matter and with each other. In addition to that, these states possess peculiar polarization properties (for instance, see Ref. [1] and references therein). Despite the fact that all macroscopic Bell states are unpolarized in the first order of intensity, they have different polarization noise. Three of them (the triplet states) have suppression of noise in one of the three polarization Stokes observables , whereas the fourth state (the singlet state or the p-scalar light) has suppression of noise in all the three observables. The analysis of fluctuations of the Stokes observables makes it possible to more appropriately classify the polarization states of light beams. The polarization quasi-probability distribution (QPD) function provides a means to calculate the mean values and the higher-order moments of the Stokes observables enabling the visualization of polarization squeezing. This polarization QPD can be reproduced from simple polarization measurement results using the method of quantum polarization tomography [2], a 3D reconstruction method.

We present a reconstruction of macroscopic Bell states prepared via high-gain PDC in two type-I BBO crystals placed into an interferometric scheme. Using the method of 3D quantum polarization tomography, the QPD functions are reconstructed for the triplet state and for the singlet state from the experimental data. We observe that the reconstructed function, which serves as a quasi-classical portrait of the quantum polarization state of light, provides a more illustrative visualization of the polarization state of light than the Stokes parameters. The reconstructed 3D distributions for the macroscopic Bell states are compared with those obtained for a coherent state with the same mean photon number. The results demonstrate squeezing in one or all Stokes parameters. Not only these results illustrate the peculiar polarization properties of the polarization-frequency entangled states, but they also advocate the utilization of this direct reconstruction method for other quantum states.

References

[1]. T. Sh. Iskhakov, M. V. Chekhova, G. O. Rytikov and G. Leuchs, Phys. Rev. Lett. 106, 113602 (2011).

[2]. V. P. Karassiov and A. V. Masalov, Opt. Spectroscopy 74, 551 (1993); Laser Phys. 12, 948 (2002); JETP 99, 51 (2004).

8440-04, Session 1

Biphoton ququarts as mixed states

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Biphoton frequency-polarization ququarts are states in which each of two photons has two degrees of freedom: frequency and polarization. Photon variables in each of these two degrees of freedom can take one of two values, corresponding to horizontal or vertical polarizations and high or low frequencies. If an experimenter decides not using frequency filters and uses only detectors unselective to photon frequencies, in theory this corresponds to averaging the ququart's density matrix over the frequency degree of freedom. Averaging means taking trace over both photons' frequency variables. Evidently, as a result, in a general case one gets the density matrix of a mixed two-qubit polarization biphoton state, even if the original frequency-polarization ququart is in a pure state. Features of such mixed states are analyzed. Their entropy S, von Neumann mutual information I, concurrence C, the Schmidt parameter K, and the degree of polarization P are found in a general form. As it should be, in a general case the entropy of the averaged state is not equal zero, which confirms that the state is mixed. The only exceptions occur when the frequency and polarization variables factorize in the original ququart's wave function and then averaging over frequencies leaves the state pure. The Schmidt parameter is shown to be related by a simple formula with the degree of polarization. But, in contrast to pure states, in mixed states the Schmidt parameter and concurrence are not related to each other at all. Thus, in the case of mixed states the Schmidt parameter K is related to classical features of states rather than to their entanglement. For some special cases we could find also the relative entropy of mixed states Srel and the degree of classical correlations defined in this case as Ccl=I-Srel.

8440-05, Session 2

Exploring mechanisms for correlated atom pair production using BEC's

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No abstract available

8440-06, Session 2

Quantum aspects of optical energy transfer in cavities and layered media

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We will study the quantized electromagnetic (EM) field in cavities and cavity like structures and develop models to describe EM energy transfer. Our starting point is based on including the quantum mechanical field-matter interaction in the traveling wave (TW) formalism with appropriate boundary conditions accounting for the interference to obtain the spatially resolved quantized field operators. This allows evaluating the Poynting vector to calculate e.g. the energy fluxes between two material bodies, the energy emitted and absorbed by a material body placed in a leaky cavity and the formation of its steady state. Furthermore, we compare the results to the conventional quantum mechanical approach based on the Lindblad master equation which inherently assumes that the perturbations to the optical modes due to the losses and interactions are small and does not describe the propagation of the EM field. The operator formalism approach contains a number of interpretational challenges related e.g. to the 'free photon' and 'confined photon' like commutation relation representations, and number of photons in the cavity. We will also address these challenges and study their potential physical implications.

8440-07, Session 2

Schmidt number for X-entanglement of photon pairs

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It has been shown recently that the spatiotemporal structure of the wavefunction of a biphoton produced in a type-I spontaneous parametric down-conversion with degenerate and collinear phase-matching has a nonfactorable X-shaped geometry, giving access to the ultrabroad bandwidth of the subharmonic, which can be exploited to achieve a photon temporal localization in the femtosecond range. In the present work we calculate a measure of entanglement for the biphoton wavefunction produced in this process, the Schmidt number.

In the limit where the width and duration of the pump pulse are much greater than the corresponding sizes of the correlations induced by the phase-matching condition, which is a typical situation for experiments with picosecond-long and millimeter-wide pulses, we obtain both approximate analytical and numerical solutions, showing the dependence of the Schmidt number K of the down-converted light passing through a filter on the filter width $\Delta\Omega$. Both analytical and numerical calculations show an almost linear growth of $K(\Delta\Omega)$ for $\Delta\Omega$ exceeding the size of the central area of the X-structured phase-matching curve. For the filter width approaching the full bandwidth of the subharmonic the Schmidt number reaches a huge value of the order of hundred thousand modes for typical nonlinear crystals. This enormous inner state space of a photon pair is available only while resolving the photon positions in the source near field and is much higher than the number available for measurements in the far-field.

[1] A. Gatti et al., Phys. Rev. Lett. 102, 223601 (2009).

8440-09, Session 2

Realization and application of strong coupling of single cesium atoms with TEM_00 and TEM_10 modes of a high-finesse Fabry-Perot cavity

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In our experiment, strong coupling of single cesium atoms with a high-finesse optical cavity (the finesse of our Fabry-Perot cavity is ~ 3.3 x 10^5 and the cavity length is ~ 86 micro-meters) has been realized in both cases of using TEM00 and TEM10 modes. The typical parameters for these two cases are (g_00, K, y) = 2Pi x (23.9, 2.6, 2.6) MHz and (g_10, K, y) = 2Pi x (20.5, 2.6, 2.6) MHz, respectively. Obviously the coupling factors (g_00 and g_10) are almost one-magnitude larger than the cavity field decay rate (K) and the transverse atomic dipole decay rate (y), therefore our system reaches exactly the strong coupling regime. It means that even only one atom or one photon entering into or escaping from the cavity will completely modify the state of whole atom-cavity system.

The first application is to adopt strong coupling of single atoms with TEM_00 cavity mode for determining the effective temperature of laser-cooled atoms, which are prepared in a magneto-optical trap (MOT) located just ~ 5 mm above the micro-cavity. The vacuum Rabi splitting is measured when cold atoms freely fall from MOT due to gravity and pass through the micro-cavity. From the probe laser's transmission signals of the atom-cavity system the velocity with which individual atom passed through the cavity is obtained. Then the effective temperature is extracted after averaging many single-atom measurements statistically and fitting experimental data theoretically. Obviously this is an alternative method for measuring the cold atoms' temperature.

The second application is to employ strong coupling of single atoms with the tilted TEM_10 cavity mode for tracking the trajectories of individual atoms, which freely fall and vertically pass through the anti-node plane of the cavity. Thanks to the tilted TEM_10 mode, instead of TEM_00 mode, the degeneracy of symmetric trajectories is eliminated completely. Under the low-field approximation the trajectories of individual atoms passing through the cavity are almost straight lines along vertical direction. This allows us to more precisely determine individual atom's trajectory along the off-axis horizontal direction. Typical spatial resolution of 100 nm is obtained in a measurement time of 10 micro-seconds, and it is much better than previous measurements.

8440-24, Poster Session

Jaynes-Cumming model of an indirect gap semiconductor cavity

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Indirect bandgap semiconductors such as silicon are not efficient light emitters because a high-momentum phonon is required to transfer an electron from the conduction to the valence band. The use of cavities to enhance the emission is a topic currently under investigation, mainly if we consider the possibility of simultaneous localization of photons and phonons. The theoretical understanding of the light-sound-matter interaction, an adequate model to explain the process is something that turns out to be essential. In this work we present a Jaynes-Cumming model to better understand the behaviour of indirect-bandgap-semiconductor (IBS) cavity, assuming that the appropriate photons and phonons could be confined simultaneously. We consider a vertical cavity consisting of an IBS phononic cavity inside of optical cavity. Using this model, we can observe collapse-revival behaviour, and we get an analytical approximate expression of the Rabi oscillation frequency for the IBS cavity.

8440-25, Poster Session

The control of entropy via interdot tunneling parameter in a quantum-dot molecule

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A quantum dot (QD) is a very interesting semiconductor device. It is a semiconductor that confines the motion of conduction band electrons in all three spatial directions, and then electrons and holes can occupy only set of discrete energies. Similar to atomic system, some interesting phenomena involving quantum coherence, i.e. lasing without inversion (LWI), electromagnetically induced transparency (EIT) and slow light, can also appear in semiconductor systems. The effect of electromagnetically induced transparency in semiconductor quantum dots have also been studied [1,2]. Because of widespread applications of semiconductor components in optoelectronics, there is strong interest in achieving such phenomena in semiconductor systems.

Recently, we studied the absorption and dispersion properties of an asymmetry semiconductor double QDs system and control the light pulse propagation using tunnel coupling [3]. Nonclassical correlations between quantum systems, which is known as entanglement, has attracted a lot of attention. Entanglement has many applications in quantum computation, quantum communication and quantum teleportation. Our main aim in this work is to study the dynamical behaviour of the entanglement between the particle and the field in an asymmetry semiconductor double QDs system (a quantum dot molecule) and control the entropy of double QD systems via inter-dot tunneling parameter and intensity of applied field. It is shown that by changing the inter-dot tunnelling parameter, the entanglement and consequently the atomic reduced entropy will change. We show that for a specific value of tunnelling, entanglement is maximum, which is dependent to the intensity of laser.

[1] C.J. Chang-Hasanian, P.C. Ku, J. Kim, S.L. Chuang, Proc. IEEE 91(2003) 1884.

[2] J. Kim, S.L. Chuang, P.C. Ku, C.J. Chang-Hasanian, J. Phys. Condens. Matter 16(2004) S3727.

[3] M. Mahmoudi and M. Sahrai, Physica E, 41, 1772 (2009).

8440-28, Poster Session

Magic-wavelength optical dipole trap of cesium and rubidium atoms

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Optical dipole trap (ODT) is a basic tool in many present cold-atom experiments that allows confinement of atoms with a long storage time. The essence of ODT is the interaction between the light-induced dipole moment of the neutral atoms and the intensity gradient of light field. Particularly, the magic wavelength ODT can cancel net light shift of desired atomic transition, therefore can avoid variance of the light shift introduced by a spatially inhomogeneous light field. Now it plays a more important role in the precision measurement especially in Sr optical clock and the state-insensitive quantum engineering.

We present analysis and calculation of the light shift of the Cs-133 6S_1/2 - 6P_3/2 transition for monochromatic trapping laser and the Rb-87 5S_1/2 - 5P_3/2 transition for both cases of monochromatic and dichromatic trapping lasers.

The magic wavelength with linearly-polarized trapping laser beam(s) for the Cs-133 6S_1/2 - 6P_3/2 transition occurs at ~ 935.6 nm, as roughly the same value people already calculated and utilized. For the Rb-87 5S_1/2 - 5P_3/2 transition, the magic wavelength with linearly-polarized trapping laser beam(s) occurs at ~ 789.9 nm; however, this magic wavelength is not practical for the opposite signs for the light shift of m_j=+/- 3/2 and m_j=+/- 1/2 states.

We also analyzed and calculated the light shift of the Rb-87 5S_1/2 - 5P_3/2 transition for dichromatic trapping lasers case, where the wavelength of one trapping laser is twice of that of another trapping laser. The magic wavelength combination for linearly-polarized lasers occurs at (784.3 nm, 1568.6 nm) and (806.4 nm, 1612.8 nm). This mechanism expands the magic wavelength conditions which permitting coherent control of atomic transition independent of the atomic motion, allow us to precisely localize and control neutral atoms with a minimum quantum de-phasing. Experimentally it can be implemented with high-efficient second-harmonic generation (SHG) of a telecom Er-doped fiber laser or fiber amplifier via periodically-poled MgO:LiNbO_3 or KTP bulk crystals.

8440-29, Poster Session

Theoretical study about the behaviour of two-level systems inside of optomechanical cavity where mechanical oscillations are induced

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The Jaynes-Cumming model (J-C model) of a two level system coupled to a single quantized mode of radiation has been used to obtain exact solutions in a variety of problems. Over the last three decades, there has been an intensive study on the solvable J-C model and its various extensions. Apart of this, the emerging fields of optomechanics seek to explore the interaction between mechanical oscillation and light. Recently, the exciting concept of optomechanical crystals has been introduced, where the defects in those structures are used to confine optical and acoustic modes. In this work we combine both fields and study the behaviour of this system inside of a cavity where an acoustic wave induced mechanical oscillations. We can see how that oscillation affects not only the collapse-revival behaviour but also the Rabi frequency oscillation.

8440-30, Poster Session

Probability density function for representing quantum states of polarized optical field in the basis of linearly polarized photons

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Formal analogies between quantum optics and classical statistical optics must be concerned reasonably, especially when talking about experimental setups containing phase plates, beam splitters etc. Although we use similar terms like state of polarization (SOP) and degree of polarization (DOP) in both cases, we have to remember that a photon, treated as a "particle" of light contains the information about its SOP in values of complex coefficients of a state vector while SOP of a plane wave is determined by a temporal shift between orthogonal polarization modes. The phase of a complex number is not the same as the phase shift of electromagnetic field polarization modes.

This come as an inspiration in authors' recent research. We ask for example if it is possible to represent an elliptically polarized plane wave in the basis of linearly polarized photons (or photons with any other arbitrary chosen phase). From mathematical point of view it is the inverse problem for the density operator describing a two-modal quantum mixed states of polarized optical field with the reduced probability density function. It is reduced because we assume that photons phase is known - it is represented by Dirac delta function in the probability distribution.

In this paper authors discuss whether this inverse problem is well posed in the sense of Hadamard. Our goal is to define a reversible integral transformation in order to represent the reduced probability density function by the density operator describing a mixed state and to analyze the uniqueness of the solution. This problem is similar to calculating Glauber-Sudarshan function when representing a quantum mixed state in the coherent states basis. However the integral transformation we search is not that easy to define. It is based on convolution and cross-correlation operations. The operator that generates this transformation is defined using the Stokes operators.

8440-32, Poster Session

Quantum unicity distance

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Shannon provided the concept of the unicity distance within classical cryptography. He gave a way of calculating approximately how many ciphertexts were required to recovery the unique encryption key. We develop this concept into the quantum context and give the definition of the quantum unicity distance.

The quantum key distribution has been proved unconditionally secure and applied in practice, though it is seem that quantum one-time pad can be achieved theoretically with the quantum key distribution, we still need to consider the repetition of key for the well-known low efficiency of the quantum key distribution. The quantum unicity distance represents the theoretical limit of how many times a key can be reused in quantum context. The quantum unicity distance of one quantum cryptography protocol can be used to measure its efficiency and the security in practice.

There are many differences between the unicity distance for the classical cryptography and the quantum cryptography. Firstly we cannot repeatedly measure one quantum state, so as one classical ciphertext can be used to verify all keys but one quantum ciphertext can only be used once, the quantum unicity distance shall be much bigger than the classical one; secondly the wrong keys may always have nonzero probability to decrypt ciphertexts into meaningful plaintexts under quantum mechanical, so the definition of the spurious key for the quantum unicity distance shall different from the one for the unicity distance. Using this different spurious key, which called quantum spurious key, we give quantum unicity distance as the length of ciphertexts which makes the amount of quantum spurious key result 0.

On the other hand, we have provided a definition of information-theoretic security for quantum cryptography based on the information-theoretic security of classical cryptography suggested by O. Goldrich. In this paper, we shall give a simple quantum encryption and a quantum probability encryption with quantum information-theoretic security, and then we calculate their quantum unicity distances. Our results show that the quantum unicity distances are much bigger than the unicity distance of classical cryptography given by Shannon.

8440-33, Poster Session

An electromagnetically induced grating in medium with tripod configuration

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In this work we studied the electromagnetic induced phase and amplitude grating in the tripod configuration. Tripod scheme is very interesting scheme because we can investigate influence of the phase ratio between two standing waves at the diffraction picture.

We have three low levels and one upper level. So on the right and left transition two standing waves was acting. The weak probe wave propagates in orthogonal direction to both standing waves. We consider optically dense homogeneously medium and our basic equations are the Lowville equations together with Maxwell equations. We take the customary approach of writing simplified wave equations for the slowly varying amplitudes. One can to notice that the transitions between lower levels were forbidden in dipole approximation.

In this problem statement there many parameters which effect to the result diffraction picture (the tune outs, phase ratios, intense of the standing field). We numerically investigated the many of these cases, especially the dependence of diffraction picture from phase ratio between two standing waves and we considered also the case when the standing waves had different intensities.

In work demonstrated the opportunity to control and manage by diffraction picture manipulating of the set of the parameters. So one can suppress any diffraction orders and amplify the others. In the simplest case when two standing waves had the even phase and intensity, as expected, the zero-order diffraction intensity is very strong.

8440-35, Poster Session

Tight binding approximation for a two-level atom Kapitza-Dirac diffraction

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We extend the study of Kapitza-Dirac diffraction in Raman-Nath regime removing the limitations put on resonance retuning.Discussing the case of extended Raman-Nath regime we develop an approximation for the case of strong standing waves which will corresponds to the well known tight-binding approximation for periodic structures. Due to the internal structure of the diffracting particles the system eigenvalues and eigenfunctions show important differences from the generally known case.

8440-10, Session 3

Coherent dynamics in energy migration at room temperature: evidence for subtle quantum-mechanical strategies for energy transfer optimization

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Electronic energy transfer (EET) is a process whereby the energy of absorbed light is transmitted between molecules. EET is a key photoinduced process for multichromophoric systems in biological photosynthesis, photovoltaic devices, photocatalysis, and sensors. For this reason in the recent years there have been many studies of EET phenomena and attempts to gain further insights into the mechanism of efficient EET. The pathways and timescales of EET for various multichromophoric systems ranging from photosynthetic complexes to conjugated polymers, to multibranched systems, are now well characterized in the frame of semiclassical theories (Förster model), in which the transfer rate can be calculated assuming incoherent quantum mechanical transitions.

However, the role of quantum coherences in determining the efficiency of energy transfer is still not well understood. This is especially true in the case of the so-called intermediate coupling, a particular regime for EET rising lot of interest because excitation moves in space, like in classical hopping mechanism, but still conserving quantum phase information.[1]

In this work we exploit two-dimensional photon echo experiments (2DPE) to observe quantum coherence dynamics in energy transfer on two evolutionarily related light-harvesting proteins isolated from marine cryptophyte algae. The data, recorded at room temperature, revealed exceptionally long lasting excitation oscillations with distinct correlations and anti-correlations even at ambient temperature. These observations provide compelling evidence for quantum-coherent sharing of electronic excitation across the 5-nm-wide proteins under biologically relevant conditions, suggesting that distant molecules within the photosynthetic proteins are ‘wired’ together by quantum coherence for more efficient light-harvesting in cryptophyte marine algae.[2]

[1] E.Collini, G.D. Scholes, Science 323 (2009) 369-373

[2] E. Collini, C.Y. Wong, KE. Wilk, P.M.G. Curmi, P. Brumer, G.D. Scholes, Nature 463 (2010) 644-648

8440-11, Session 3

Engineering quantum communication systems

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Quantum communications can provide almost perfect security through the use of quantum laws to detect any possible leak of information. We discuss critical issues in the implementation of quantum communication systems over installed optical fibers. Our group is an experimental group and we have been optimizing several schemes for quantum communications implementation. We do not work in the development of quantum cryptographic protocols but we have been using our systems to test and validate cryptographic protocols developed by other research groups.

We use stimulated four-wave mixing to generate single photons and by tuning the separation between the pump and the signal we adjust the average number of photons per pulse. We measure and model the source statistics and find that the source statistics goes from a thermal to Poisson distribution with the increase of the pump power. We have been developing detailed theoretical models for the four-wave mixing process in optical fibers in a low power regime. We have been able to validate most of the results experimentally. We propose an effective nonlinear coefficient to account for the loss of correlation between the pump and signal polarization evolution when there spectral separation is increased.

We have been generating entangled photons pairs through spontaneous four-wave mixing. We have used different type of fibers to approach the maximum value of the Bell inequality. We obtain the strongest violation with a 150 meters long high nonlinear fiber with a nonlinear coefficient of 10.5 W^(-1) km^(-1). We model the impact of polarization rotation, attenuation and Raman scattering and find optimum configurations to increase the degree of entanglement.

We encode information in the photons polarization and we assess the use of wavelength and time division multiplexing based control systems to compensate for the random rotation of the polarization during transmission. We show that time division multiplexing systems provide a more robust solution considering the values of PMD of nowadays installed fibers. In WDM based control systems the loss of correlation between the reference and data signals is an intrinsic and very limitative impairment. Its contribution to QBER increases with the propagation distance, and is highly dependent on the value of the fiber PMD. We also evaluate the impact on the quantum channel of co-propagating classical channels, and find guidelines for adding quantum channels to installed WDM optical communication systems without strongly penalizing the performance of the quantum channel.

We discuss the process of retrieving information from the photons polarization. We model the major impairments that limit the speed and distance of the quantum channel. We show that with a proper polarization control system the major constrained to the increase of the system reach arise from optical attenuation. Finally, we model theoretically the QBER and experimentally perform an assessment of the system quality through QBER measurements.

8440-13, Session 3

Integrated devices for quantum information and simulation with polarization encoded qubits

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It has been recently demonstrated that ultrafast laser writing (ULW) allows to realize integrated devices able to support and manipulate polarization encoded qubits [1]. By the ULW technique a femtosecond laser is focused on a glass substrate inducing a variation of the glass refractive index in the region around the focus: by moving along the three orthogonal directions the glass substrate with respect to the laser beam it is possible to directly write waveguides inside the chip. Thanks to this method both polarization dependent and independent devices can be realized. In particular, the maintenance of polarization entanglement was demonstrated in an integrated beam splitter [1] and an integrated CNOT gate for polarization qubits was realized and characterized [2]. This last result was made possible thanks to the integration, based on femtosecond laser waveguide writing, of partially polarizing beam splitters on a glass chip. We characterized the logical truth table of the quantum gate demonstrating its high fidelity with respect to the expected one. We could also show the ability of the gate to transform separable states into entangled ones and viceversa.

In a more recent experiment we exploited integrated optics for quantum simulation tasks: by adopting the ULW technique an integrated array of symmetric polarization independent beam splitters was built to realize a discrete quantum walk circuit [3]. In this way, for the first time, we could investigate how the particle statistics, either bosonic or fermionic, influences a two-particle quantum walk. Such experiment was realized by injecting two-photon entangled states into the integrated photonic circuit. Hence polarization entanglement was exploited to simulate the bunching-antibunching feature of non interacting bosons and fermions. On this purpose we adopted a novel three-dimensional geometry for the waveguide circuit, allowing accurate polarization independent behaviour and maintaining a complete control on both phase and balancement.

[1] L. Sansoni, F. Sciarrino, G. Vallone, P. Mataloni, A. Crespi, R. Ramponi, and R. Osellame, Polarization entangled state measurement on a chip, Physical Review Letters 105, 200503 (2010).

[2] A. Crespi, R. Ramponi, R. Osellame, L. Sansoni, I. Bongioanni, F. Sciarrino, G. Vallone, and P. Mataloni, Integrated photonic quantum gates for polarization qubits, Nature Communications DOI: 10.1038/ncomms1570, 1 (2011).

[3] L. Sansoni, F. Sciarrino, G. Vallone, P. Mataloni, A. Crespi, R. Ramponi, and R. Osellame, Two-particle bosonic-fermionic quantum walk via 3d integrated photonics, Arxive quan-ph, 1106.5713 (2011), Phis. Rev. Lett., to appear.

8440-31, Session 3

Quantum public-key encryption protocols with information-theoretic security

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Most of the widely used public-key encryption schemes will be broken by quantum computers, therefore, they are not secure in the era of quantum computing. Some quantum public-key encryption schemes have been given, but the best security achieved by them is bounded information-theoretic security. This kind of security means that the number of bits which can be information-theoretic securely encrypted has an upper bound. In the former works, this bound is about the number of bits of private keys, so this is not sufficient for practical use. Widely accepted quantum public-key encryption schemes with information-theoretic security have not been proposed. We present here some quantum public-key encryption protocols orienting classical messages, and prove their information-theoretic security.

We first introduce an information-theoretic secure scheme without the help of entanglement states. For the key generation step, Bob generates his private and public keys, and sends the public key to the public register. The private key is a multi-output Boolean function F, and the public key is a pair of quantum states and classical bits. We present a way to efficiently generate the Boolean function. We use this classical-quantum pair as the public key, instead of the quantum state alone, because in this case, Bob can decrypt the ciphertext in a convenient manner. In the bounded information-theoretic secure schemes mentioned at the beginning, the public key does not change. However, in our scheme, Bob may generate many public-keys with the same private key F.

In the encryption phase, if Alice wants to send one bit message to Bob, she should get one of Bob's public keys from the public register, and does some unitary operation on the quantum part of the public key, then send this changed quantum part together with the original classical part to Bob. The unitary operation depends on her message. In the decryption phase, Bob first applies the private key (Boolean function F) to the classical part received, then does some unitary operation according to the result get from the calculations, finally he can get the message.

The adversary who wants to eavesdrop the message that Alice sends to Bob cannot get unnegligible information of private key from the public key. He also cannot get any information of the plaintext from ciphertext. We give detailed proof of the security of the scheme. In this part, we use the operator-sum representation of quantum operations and the properties of trace distance, and finally prove information-theoretic security of the scheme. This scheme can be implemented with current technique, using a series of photons.

For the second protocol, we first introduce two n-qubit quantum states and prove the indistinguishability and trapdoor property of them. Then we construct a trapdoor one-way function based on the two states, and suggest a bit-oriented quantum public-key encryption scheme. This scheme is then proved to be information theoretic secure under chosen plaintext attack. Finally, we extend the quantum public-key encryption scheme to multi-bit-oriented one.

8440-34, Session 3

Entanglement swapping with two and three pairs of entangled qubits in the presence of noise

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In 90s years in articles [1] [2] were shown the method of the generation of en-tangled states of particles, that never physically interacted with each other. This method is called «entanglement swapping».

The first experimental realization of entanglement swapping with two pairs of entangled photons was performed in 1998 [3]. That paper has shown the principal possibility of this process. In 2009 Chao-Yang-Lu at al. [4] reported the first experimental demonstration of Greinberger-Horne-Zeilenger (GHZ) entanglement swapping with three pairs of entangled photons. The calculations which were performed in these articles were done with pure states of photons.

Objective of this work is the research of final state of photons on the experi-ment schemes [3] and [4] , in the presence of white, color and both white and color noises in the initial states of photons. There was developed a computer program to find the final state of photons. With the help of this program the density matrices and density operators of the final photon states were obtained. The comparative analysis of numerical parameters of the initial and final states of photons was done. Results of the analysis of photon initial states were taken from [5].

The main results of our research are:

1. Level of noise in final state is higher, than in initial state

2. If noise in initial entangled states are higher than some critical level, final states will be unentagled. The range of parameters of systems of initial states, when we have such situation were obtained.

The results of this work can be used to analyze the experiments' efficiency with entanglement swapping in terms of noise contribution in the initial entangled states to final entangled state.

References:

1.Bose, S., V. Vedral, and P. L. Knight, Phys. Rev. A 57, 822 (1998).

2.M. Zukowski, A. Zeilinger, M. A. Horne, and A. K. Ekert, Phys. Rev. Lett. 71, 4287 (1993).

3.J. Wei-Pan, D. Bouwmeester, H. Weinfurter, Phys. Rev. Lett. 80, 3891 (1998)

4.Chao-Yang Lu, T. Yang, and J. Wei Pan, Phys. Rev. Lett. 103, 020501 (2009)

5.Ivan S. Dotsenko, Volodymyr G. Voronov, Optics Communications Volume 282, Issue 14, 15 July 2009, 2889

8440-15, Session 4

Orbital angular momentum for quantum information processing

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Among all degrees of freedom offered by single photons, the orbital angular momentum (OAM) has a great potential in the quantum information field, as it provides a natural choice for implementing single-photon qudits, the units of quantum information in a higher dimensional space. This can be an important practical advantage, as it enables higher security in quantum cryptographic protocols, as well as implications in fundamental quantum mechanics theory. Moreover, the combined use of different degrees of freedom of a photon, such as OAM and spin, enables the implementation of entirely new quantum tasks. Recently we have manipulated the polarization and OAM degrees of freedom to generate a ququart encoded in a single photon [1, 2]. Since we exploit two different degrees of freedom of the same particle, we refer to hybrid-ququart states. Such results have been achieved through the q-plate device [3, 4], which couples the spinorial (polarization) and orbital contributions of the angular momentum of photons.

The capacity to manipulate with high reliability all quqart states encoded in a single photon enforce the achievement of the quantum state engineering of ququart to direct towards the implementation of new quantum information protocols and more robust communication procedures. Interestingly, states belonging to two such basis shows entanglement between polarization and OAM and are naturally generated by the q-plate device. In particular, single-photon encoded ququart states could be adopted for the implementation of a quantum key distribution protocol without a reference frame recentely proposed [5], as well as for the implementation of quantum contextuality tests [6] and alignement-free protocols [7]. By exploiting the bidimensional space of polarization and different subspaces of OAM, a further extension can be the generation of other qudit states, i.e. quantum states in dimension d.

[1] E. Nagali, L. Sansoni, L. Marrucci, E. Santamato, F. Sciarrino, Phys. Rev. A 81, 052317 (2010).

[2] E. Nagali, D. Giovannini, L. Marrucci, S. Slussarenko, E. Santamato, and F. Sciarrino, Phys. Rev. Lett., 105, 073602 (2010).

[3] E. Nagali, et al., Phys. Rev. Lett. 103, 013601 (2009).

[4] E. Nagali, et al., Nature Photonics 3, 720(2009).

[5] C. E. R. Souza, Phys. Rev. A 3, 032345 (2008).

[6] A. Cabello, V. D'Ambrosio, E. Nagali, F. Sciarrino, Phys. Rev. A 84, 030302 (2011).

[8] V D'Ambrosio, E. Nagali, S. P. Walborn , L. Aolita, S. Slussarenko, L. Marrucci, and F. Sciarrino (in preparation)

8440-16, Session 4

Spatially entangled 4-photon states from periodically poled KTiOPO4

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Spontaneous parametric down conversion is a convenient process to generate multi-photon states that are fundamental resource for quantum metrology and quantum imaging. We create spatially entangled 4-photon states at 826.4 nm wavelength by pumping a 2 mm long periodically poled KTP crystal with 2 ps laser pulses. The intense pump enables a non-negligible rate of 4-photon events, which are either 2 independent pairs, created by spontaneous emission, or a genuine 4-photon state created by stimulated emission of a second photon pair.

We demonstrate experimentally how spatially entangled 4-photon states can be distinguished from double pairs. The spatial domain offers the distinct advantage over other approaches that high spatial resolution can be easily achieved by selecting appropriate lenses and apertures. We reach visibilities of 37% of the 4-photon state for an experimental pump beam waist of 80 µm. The visibility depends strongly on the number of available spatial and temporal modes, which can be controlled by the focus of the pump beam, the size of the detector aperture, and filtering in the frequency domain. We will present the result of visibility dependence and the joined spatial amplitude of the two-photon state on the focusing conditions of the pump beam.

8440-17, Session 4

A scaling-limit approach to the theory of laser transition

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An analytic solution for the two-level laser problem is presented, which enables a detailed discussion of the conditions for a sharp laser transition. It is known that lasing is associated with the onset of Poissonian photon statistics (coherent light). In order to verify this coherent regime criterion, one has to check, in principle, an infinity of conditions, either on the elements of the photonic density matrix or on a particular sequence of expectation values, like the photonic correlation functions. But in experimental situations or in numerical simulations, only a finite set of conditions can be checked, and it is quite common to limit oneself to the test on the second-order correlation function becoming equal to 1, as a symptom of lasing. The advantage of an analytic solution is that it allows a full verification of the onset of coherence. It turns out that the laser transition occurs only in the limit in which the rate of cavity losses scales as the square of the light-matter coupling, and both go to zero [1]. This scaling limit is a generalization of the one discussed in Ref. [2]. We also show that the condition for the second-order correlation function is met before the higher correlators reach their coherent values and therefore it is not a sufficient criterion for lasing. The same scaling limit procedure is shown to describe correctly the laser transition in the Scully-Lamb random injection model too.

[1] P. Gartner, Phys. Rev. A 84, 053804 (2011).

[2] P.R. Rice, and H.J. Carmichael, Phys. Rev. A 50, 4318 (1994).

8440-18, Session 4

Geometric phases in adiabatic Markovian dynamics

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Recently, we extended the concept of adiabaticity from closed quantum systems to the case of open systems undergoing Markovian dynamics, and derived a corresponding adiabatic theorem [1]. The central idea behind our approach is that adiabaticty in quantum mechanics concerns quasistatic evolution, where under sufficiently slow changes of the generator of the dynamics, a stationary state evolves so as to remain stationary with respect to generator as it changes. In the case of closed systems, the generator is the Hamiltonian, and the stationary states are those that belong to its eigenspaces. In the case of Markovian dynamics, the generator is the Lindbladian, and the natural generalization of the concept of eigenspace is a noiseless subsystem with a minimal noisy cofactor. Unlike previous attempts to define adiabaticity for open systems, this approach is physically motivated and provides a simple, intuitive picture at the underlying Hilbert-space level, linking the notion of adiabaticity to the theory of noiseless subsystems. In this talk, I will review the theory of adiabatic Markovian dynamics and present new results concerning the geometric phases that occur when the stationary states residing in a pair of noisless-noisy subsystems are transported adiabaticially around a loop [2]. The new type of holonomies that we obtain generalize the previously known holonomies for subspaces and mixed-states, reducing to one or the other in special limiting cases. We have obtained a simple closed-form expression for the gauge potential governing the transformation in the noiseless subsystem. Our framework captures both cyclic and non-cyclic evolutions and suggests new applications for quantum computation.

[1] O. Oreshkov and J. Calsamiglia, PRL 105, 050503 (2010).

[2] O. Oreshkov and E. Sjoqvist, in preparation.

8440-19, Session 4

Two-photon experiments in the frequency domain

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We report the study of two-photon interference in the frequency domain. Bell and Hong-Ou-Mandel experiments are investigated. Those experiments involve the manipulation of photons in the frequency domain, using off-the-shelf telecommunication components such as electro-optic phase modulators and narrow-band frequency filters. In the first experiment, photon pairs entangled in frequency are created and separated, so that each photon passes through an independent electro-optic phase modulator. Variation of the radio-frequency parameters of the modulation gives rise to a well-controlled Bessel-shape two-photon interference pattern in the frequency domain. This is efficiently measured with narrow-band frequency filters and superconducting single photon detectors. Experimental measurements exhibit high visibilities (over 99 percent both for net and raw visibilities) and allow the optimal (as theoretically proven) violation of a Bell inequality (by more than 18 standard deviations). The latter experiment is a Hong-Ou-Mandel experiment in the frequency domain. We show that a grating (spatial domain) or a phase modulator (temporal domain) can be seen as a "frequency beam splitter". A broadband spectrum of photon pairs is divided into two interleaved frequency combs, each of them being an input for the so-called beam splitter. Our calculation shows clear photon anti-bunching behaviour.

8440-12, Session 5

Macroscopic entangled state of light

T. S. Iskhakov, M. V. Chekhova, G. Leuchs, Max Planck Institute for the Science of Light (Germany)

Entanglement is one of the most exciting and unique features of quantum physics. It is commonly believed that entanglement can be only manifested by microobjects such as photons, electrons, atoms etc. The most popular example of a bipartite entangled, i.e. interdependent, quantum system is the two-photon Bell state. This is the maximally entangled state of two qubits, which is manifested in perfect correlations between them. However, it contains only two photons. At the beginning of this century there were several attempts to increase the number of entangled photons. The record number of entangled photons detected in the experiment is twelve [1].

In this work we generate the bright analog of the singlet Bell state. The state contains more than 10^5 photons per pulse and is therefore macroscopic. We experimentally demonstrate that it is entangled by violating a nonseparability criterion formulated in [2]. Our macroscopic state is described by the same Hamiltonian as the two-photon Bell state, and we produce it in experiment in a similar way, via the quantum interference of two orthogonally polarized two-color squeezed vacuums. The difference is that our squeezed vacuum is produced via high-gain parametric down-conversion. As prepared, the state is pure but still completely non-polarized, in the sense that all moments of all polarization observables are zero. Moreover, the noise of all polarization observables is reduced below the shot-noise level. Due to the technical limitations in the detection (finite quantum efficiency of the detectors and losses in the optical channel), the state becomes mixed but still exhibits properties witnessing that it is not separable.

These results, as well as certain theoretical considerations, make us conclude that this state is a candidate for macroscopic Bell tests. Its high brightness opens prospects for efficient interaction with matter and possible quantum memory applications. In addition, the high sensitivity to losses makes this state applicable in metrology.

[1] H. S. Eisenberg et al., Quantum Entanglement of a Large Number of Photons, Phys. Rev. Lett. 93, 193901 (2004).

[2] Ch. Simon and D. Bouwmeester, Theory of an Entanglement Laser, Phys. Rev. Lett 91, 053601 (2003).

8440-14, Session 5

Public-key encryption and authentication of quantum information

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Public-key cryptosystem is a well-studied area of classical cryptography. In this paper, we investigate quantum public-key cryptosystems in which both the public key and the message are quantum states. It is considered from the two directions: public-key encryption scheme for quantum message, public-key authentication scheme for quantum message.

Our public-key encryption scheme for quantum message is achieved by combining a symmetric-key encryption scheme for quantum message with a public-key encryption scheme for classical message.

In 2008, Kawachi and Portmann proposed a quantum asymmetric-key model for quantum message which uses quantum public key. In their model, one private key is corresponded to only one quantum public key. While copies of quantum public key are going to be published, the amount of copies must be limited, because the private key can be extract from enough copies of quantum public key. In this paper, their scheme is improved, and one private key is corresponded to several quantum public keys which are generated independently. In our scheme, Bob's private key is a function and he can generate several different quantum public keys from this private key. Bob sends these quantum public keys to his public-key register. When Alice wants to send a quantum message to Bob, she firstly gets one quantum public key from Bob's public-key register, and then encrypts a quantum message using this public key. Because these quantum public keys are generated independently, the attacker cannot obtain enough copies of the same public key and cannot extract useful information. We demonstrate our public-key encryption scheme is information-theoretical security.

We propose a general construction of quantum public-key authentication scheme by combining a symmetric-key authentication scheme for quantum message with a public-key encryption scheme for classical message.

In 2002, Barnum et al. proposed a symmetric-key authentication scheme for quantum message in which the key is classical. We extend it to a quantum public-key authentication scheme in which the public key is quantum state. A concrete construction is given by combining their symmetric-key authentication scheme with a public-key encryption scheme for classical message. In this concrete scheme, quantum message is both encrypted and authenticated using quantum public keys. This scheme can also be seen as an extended version of our public-key encryption scheme. As an encryption scheme, it maintains information-theoretical security; as an authentication scheme, its error probability decreases exponentially in the security parameter.

8440-22, Session 5

Raman laser cooling below a photon recoil with alkali-earth elements

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We numerically investigated the four-level scheme, for one there is three-level cascade on the left hand and one level on the other hand. Such scheme is appropriative for group of atom - alkali-earth atoms and Ytterbium. First we considered the system analytically for Schrödinger equations. We use the approach, namely, we supposed that the population on the middle level of the left cascade stay very small. For this approach the analytical results were obtained for classical fields acting on the transitions. The transition between the lowest level in cascade and the right level is the clock transition.

Numerically investigations were realized for probability amplitudes approaches and for density matrix formalism. The results of calculations shown that the Raman cooling mechanism allow reach below one recoil energy keeping the quite large number of cold from initial distribution (in average ratio inicial atom inside narrow energy interval to cooling atom equal about four time). For each pulse we determined the duration in order to this pulse was pi-pulse. So this way one can to reduce the number of cooling circles.

We investigated also different form of pulse shapes and different parameters of scheme. So the appropriative parameters for calcium and magnesium atoms come quite effective cooling for several circles. Besides we was interesting compare our result with experimental data for these atoms published another authors and we have good agreement. Besides we compare our results with results for quenching cooling technique and shown that in case near equidistant levels the Raman cooling was more valid.

8440-23, Session 5

Towards linear optical detection with single photon sensitivity at telecom wavelengths

S. Jahanmirinejad, A. Fiore, Technische Univ. Eindhoven (Netherlands)

Standard linear optical detectors have a maximum sensitivity in the few hundreds of photons range, limited by amplifier noise. On the other hand, single photon detectors, which are the most sensitive detectors, are strongly nonlinear: One or more photons result in the same output signal. Photon number resolving (PNR) detectors, which have the ability to discriminate the number of photons in a weak optical pulse, are of great importance in the field of quantum information processing and quantum cryptography. Moreover, a PNR detector with large dynamic range can cover the gap between these two detection modes. Such detectors are greatly desirable not only in quantum information science and technology, but also in any application dealing with low light levels. In this work, we propose a novel approach to photon number resolving detectors based on spatial multiplexing of nanowire superconducting single-photon detectors. In the proposed approach, N superconducting nanowires, each connected in parallel to an integrated resistor, are connected in series. Photon absorption in a nanowire switches its bias current to the parallel resistor, forming a voltage pulse across it. The sum of these voltages, proportional to the number of absorbed photons, is measured at the output. The use of a cryogenic preamplifier with high input impedance for the read-out increases the linearity, the signal to noise ratio, and the speed. With this combination, we expect to be able to count up to few tens of photons with high fidelity, excellent timing resolution, and very high sensitivity in the telecommunication wavelength range.

SPIE Photonics Europe

Hot Topics I

European Commission address: Innovating in Photonics in Horizon 2020

Thierry Van der Pyl, Director, Directorate G “Components and Systems”, Information Society and Media Directorate General European Commission

This talk will focus on the upcoming Horizon 2020, the EU’s new Framework Programme for Research and Innovation for 2014 to 2020, with a particular emphasis on the role of photonics research and innovation.

Photonics is recognised as one of the European Union’s six Key Enabling Technologies. Nevertheless, there are still many challenges in translating excellent research into innovation potential and economic growth and job creation. The speaker will give an overview of the main photonics challenges in Horizon 2020 and will address some of the main ingredients needed for the success for photonics research and innovation, including the key role to be played by close partnerships, between industry and academia, between public and private sources of finance and between the European, national and regional levels.

Breakthroughs in nonlinear optics: new waveguides, new nonlinearities, new directions in ultrafast science

John M Dudley, Univ. de Franche-Comté, CNRS Institut FEMTO-ST, Besançon, France

The years 2010 and 2011 saw worldwide celebrations of the invention of the laser and the birth of nonlinear optics. These coupled anniversaries remind us how the fields of laser source development and nonlinear optics have been natural partners now for over half a century, and how this partnership has impacted on all fields of science and technology.

The purpose of this talk in the first months of 2012 will be to look to the future, and to survey a broad selection of new breakthroughs in nonlinear optics. We will discuss in particular how developments in new materials and new classes of photonic waveguide are leading to fundamental advances in the understanding of nonlinear light-matter interactions and new applications across many different fields. We focus especially on development in ultrafast nonlinear photonics, and consider how these advances are motivating unexpected new directions of research with surprising applications for other fields of physics.

Next generation fibre sensors

Kyriacos Kalli, Nanophotonics Research Laboratory, Cyprus Univ. of Technology, Cyprus

Fibre sensors have been the subject of vigorous research activity for more than forty years, but have yet to reach their anticipated, ground-breaking role in real-world applications. This challenge has gained a new momentum with the development of innovative fibre types and the emergence of novel sensing concepts. This is particularly the case for microstructure optical fibres, where a myriad of fibre geometries are possible; when coupled with new host materials, infusion of the holey structure and doping, increased functionalisation is possible for sensing. A further impetus has been given to conventional optical fibre sensors; the advent of femtosecond lasers has added extraordinary versatility and flexibility to sensor development. Both sensor inscription and fibre micromachining are readily possible on a common platform, offering the opportunity to tailor the mechanical and optical properties of sensor devices.

In this plenary session, the latest developments in fibre sensors will be presented, with particular consideration to the versatility of optical fibre sensors. The development of embedded, advanced microstructure fibre grating sensors in glasses and polymers will be presented. Recent advances in infiltrated microstructure fibre sensors using ferrofluids for magnetic field measurements will be discussed, as will surface plasmon sensors for measuring low refractive indices required for bio-photonics and sensors tailored for measurements in harsh radiation environments. Moreover, the use of femtosecond lasers in developing vectorial fibre sensors and diffractive micro-optical elements for sensing will be reviewed. Finally, we will consider what the future may hold for sensor development.

Advances in high-power fiber laser systems

AndreasTünnerman, Friedrich Schiller Univ. Jena, Institute of Applied Physics, and Fraunhofer Institute for Applied Optics and Precision Engineering, Germany

Most recently, rare-earth-doped fibers have established themselves as an attractive and power scalable solid-state laser concept in science and industry. Using advanced large mode area fibers, in continuous-wave operation output powers in the 10 kW-regime with diffraction-limited beam quality at electrical to optical efficiencies of 30 percent have been demonstrated. In the pulsed regime average powers in the order of 1 kW even for femtosecond fiber laser systems have been reported, peak powers of fiber lasers exceed the GW-level. Novel beam combination techniques allow for further power scaling.

In this contribution the state of the art in solid state laser technology operating at high average powers with inherent high efficiencies is reviewed. The prospects for future developments will be discussed.

SPIE Photonics Europe

Hot Topics II

Optofluidics for solar energy

Demetri Psaltis, École Polytechnique Fédérale de Lausanne, Switzerland

Optofluidics refers to a class of devices and techniques that combine optics and fluidics. Biophotonics has been a major application of optofluidics partially because in biology we normally use light to make measurements of entities suspended in liquids. Therefore biophotonics naturally combines fluids and optics. The same thing is true in the field of solar fuels where generally chemicals in liquid form are exposed to sunlight which catalyzes or thermally accelerates a chemical reaction that generated useful fuels. The design of a solar fuel system requires the simultaneous optimization of the optical and fluidic properties of the system. We will discuss how optofluidic solar fuel systems [1] that rely on microstructured components with dual, optical and fluidic functionality can improve the fuel generation efficiency.

[1] Erickson D, Sinton D, Psaltis D, Optofluidics for energy applications, Nature Photonics, Vol. 5, pp. 583-590, October 2011

Photoacoustic tomography: ultrasonically breaking through the optical diffusion limit

Lihong V. Wang, Optical Imaging Lab., Washington Univ., United States

Photoacoustic tomography (PAT), combining optical and ultrasonic waves via the photoacoustic effect, provides in vivo multiscale non-ionizing functional and molecular imaging. Light offers rich tissue contrast but does not penetrate biological tissue in straight paths as x-rays do. Consequently, high-resolution pure optical imaging (e.g., confocal microscopy, two-photon microscopy, and optical coherence tomography) is limited to depths within the optical diffusion limit (~1 mm in the skin). Ultrasonic imaging, on the contrary, provides good image resolution but suffers from poor contrast in early-stage tumors as well as strong speckle artifacts. In PAT, pulsed laser light penetrates the tissue and generates a small but rapid temperature rise, which induces emission of ultrasonic waves due to thermoelastic expansion. The ultrasonic waves, ~1000 times less scattering than optical waves in tissue, are then detected to form high-resolution images at depths up to 7 cm, breaking through the optical diffusion limit. Further depths can be reached by using microwaves or RF waves as the excitation source. PAT, embodied in the forms of scanning photoacoustic microscopy or photoacoustic computed tomography, is the only modality capable of imaging across the length scales of organelles, cells, tissues, and organs with consistent contrast. Such a technology has the potential to enable multiscale systems biology and accelerate translation from microscopic laboratory discoveries to macroscopic clinical practice. PAT may also hold the key to the earliest detection of cancer by in vivo label-free quantification of hypermetabolism, the quintessential hallmark of cancer. The technology is commercialized by several companies.

Hot Topics III

Technologies and equipment used in the manufacturing of silicon solar cells and thin-film panels

Finlay Colville, SOLARBUZZ, United Kingdom

The solar industry has seen explosive growth in recent years, driven by attractive government policies and aggressive manufacturing expansions. As a result, the solar industry has developed into a multi-billion dollar industry, with a strong focus on technology including novel methods for manufacturing solar cells and panels. There are two main technology approaches competing to satisfy industry demand. The dominant technology uses polysilicon wafers that are processed into PV cells and then interconnected into panels. The competing approach involves depositing thin film materials typically on large glass sheets. Each approach is differentiated in both its manufacturing process flow and its equipment supply-chain.

This presentation will provide a review of each of these technologies, covering the value-chain for manufacturing and the different type of equipment used at each stage. New technologies and trends will also be addressed, including what impact they may have on the solar industry in providing higher efficiencies or lower manufacturing costs and how this may help the industry in achieving widespread grid-parity out to 2020.

Recent advances in solid state lighting

Berit Wessler, OSRAM, Germany

Solid-state light sources, i.e. light-emitting diodes (LED) and organic light emitting diodes (OLED), are starting a new era in lighting as they are on their way to outperform almost all other light sources in terms of efficiency and provide unique properties such as long lifetime, instant-on and color tunability. Theoretically more than 50% of electrical energy used for lighting could be saved with advanced LED technology which, in turn, will lead to a massive reduction of carbon dioxide emissions.

An overview on the technology innovations of the last years will be given with respect to the whole product value chain from LED chips to fixtures as well as an outlook to the future challenges which need to be solved to enable the broad penetration of Solid State Lighting (SSL) in the lighting market.