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8070-01, Session 1

Plasmon-mediated emission of THz light by metallic nanoparticles

W. L. Barnes, The Univ. of Exeter (United Kingdom)

No abstract available

8070-02, Session 1

Photonic waveguiding structures with loss and gain

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Passive real-world waveguiding structures are inevitably lossy, and some of them, such is plasmonic waveguides, exhibit very strong attenuation. The losses that occur in such structures can be compensated by including the active components with gain. In this paper we discuss properties of waveguiding structures with the complex dielectric permittivity distributed across their cross-section. In particular, we focus on the existence of modes that exhibit balance between loss and gain and that can propagate without attenuation provided the suitable conditions are satisfied. Similar structures have been recently investigated as photonic analogues of quantum mechanical structures with parity-time (PT) symmetry. With increasing gain and loss, effects analogous to PT symmetry breaking take place.

Specifically, we examine power transmission in the structures with a balance of loss and gain supporting lossless propagation of two modes. We demonstrate that when both modes are excited simultaneously, the total transmitted power is not conserved as the modes propagate along the waveguide. We also have shown that even if one of the modes propagates with gain, the maximum attainable transmitted power may be limited by back-reflections from the boundary or from the interface with the passive output waveguide. We also discuss the conditions for the existence of an un-attenuated propagation of a confined surface mode supported by the gain/loss nature of the photonic structures.

8070-03, Session 1

Plasmon-mediated resonance energy transfer near metal nanostructures

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

A theory of resonance energy transfer (RET) between donor and acceptor molecules (or quantum dots) situated near a plasmonic nanostructure is presented that incorporates, in a unified way, nonradiative and radiative transfer channels while maintaining energy balance between transfer, dissipation and radiation. A new mechanism is identified - plasmon-enhanced radiative transfer - that dominates RET in a wide range of parameters. Numerical calculations performed for molecules near spherical Ag nanoparticle indicate that RET is determined by competition between plasmon enhancement and metal quenching and its magnitude is highly sensitive to molecules positions. There are regions in parameter space where plasmon-mediated RET can be either enhanced or reduced relative to Foerster transfer, consistent with experiment. A comparison between our theory and previous models is performed.

8070-04, Session 1

The diabolo nanoantenna as a plasmonic element of metamaterials

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We recently showed by numerical simulations that a gold nanostructure of the form of a 2-D diabolo has the interesting property that it can serve as a nanoantenna for enhancing and confining the magnetic optical field at the metal constriction (1,2). It was shown that at an overall size of 310 nm and a 20 nm wide constriction such a structure can have at a resonance wavelength of 2.9 µm an enhancement of the magnetic field intensity of 2900 (2). This fact makes the structure interesting as an element of a metamaterial requiring elements of a size small compared to the vacuum wavelength. We noticed that below the resonance frequency, the near field distribution of the diabolo is similar to the near field distribution of an extended dipole but there is a difference. The magnetic field of the induced dipole has the opposite orientation as compared to the one of an electric dipole. In this sense the diabolo can be considered as an electric mirror dipole. A plane wave can be synthesized by a superposition of dipole fields. It is therefore plausible that a superposition of mirror dipoles should lead to a plane wave with a negative phase velocity. We therefore conclude that the diabolo may be considered as an interesting element of a metamaterial with a negative refractive index. More generally we consider a constriction in a metal nanostructure with its opposing concave corners as an inductive element, opposing convex tips as a capacitive element and a thin wire as a resistive element. Passive networks of these structures like parallel and series resonators are feasible. The diabolo itself can be considered as a series LC resonator with the metal constriction serving as the inductive element and its edges at both sides as a parasitic capacitive element. It differs e.g. from the well known split ring resonator which can be considered as a parallel LC resonator with the ring serving as the inductive and the gap serving as the capacitive element. We think that an advantage of the opposite concave corners as an inductive element is that it can be made much smaller than a loop of a similar inductance. Single metal structures of this type as well as arrays of such structures can be fabricated by lithographic techniques such as electron beam lithography and focused ion beam lithography as well as by modifications of nanosphere lithography (3).

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3) U.C. Fischer, J. Heimel, H.-J.Maas, M.Hartig, S.Hoeppener, H. Fuchs, Surf. Interface

Anal 2002, 33, 75-80.

8070-05, Session 2

Bloch modes of optical fishnets

P. Lalanne, Lab. Charles Fabry (France)

Today, our common understanding of negative-index optical metamaterials is based on fully-vectorial electromagnetic calculations, including field averaging, Bloch mode approaches, multipole expansion, and inversion of scattering parameters. These approaches accurately predict the light transport, but are often unintuitive, hindering the design process required to incorporate metamaterials into new optical technologies. Here, analogously to the lumped element model that deeply impacts the design of metamaterials at

microwave frequencies, we aim at providing an analytic description for the negative index of optical fishnets. For that purpose, we abandon classical homogenisation approaches, and we adopt a microscopic model in which we track the light as it propagates and scatters through the fishnet channels, as a fluid flows in a multi-channel system. The dynamics involves two channels, a longitudinal one formed by subwavelength air holes and a transversal one formed by metal-insulator-metal (MIM) gap-SPP waveguides. Through simple coupled-mode equations that describe how the channels couple and exchange their energies, we derive analytical expressions for the fundamental effective index of the fishnet Bloch modes and show how negative values appear over a broad spectral range. In addition to corroborate previous analysis, the model provides a comprehensive framework that allows an in-depth analysis of the physical origin for negative index appearance in fishnets. Interestingly too, the model allows us for a straightforward analysis of loss compensations, a vital issue for metamaterials in the near-infrared and visible wavelength ranges.

8070-46, Session 2

Nonlinear and tunable metamaterials

Yuri Kivshar, The Australian National Univ. (Australia)

We review the theoretical and experimental results on tunability and nonlinear response of metamaterials, in particular the results obtained at the Nonlinear Physics Center of the Australian National University (http://wwwrsphysse.anu.edu.au/nonlinear/). We develop the approach based on nonlinear response of metamaterial elements, and we demonstrate both theoretically and experimentally dynamic tunability of the magnetic resonance of SRRs with varactor diodes at microwave frequencies. Based on the properties of single SRRs, we fabricate and study nonlinear metamaterials composed of split-ring resonators where a varactor diode is introduced into each resonator so that the magnetic resonance can be tuned dynamically by varying the input power. In addition, we discuss a variety of other intriguing effects and phenomena associated with the negative index of refraction and the specific properties of backward waves, including (i) nonlinear electric metamaterials, (ii) tunability via engineering of near-field interaction, (iii) nonlinear magnetoelastic interaction in metamaterials.

8070-06, Session 2

Unified approach for retrieval of effective parameters of metamaterials

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It is convenient to describe the properties of metamaterials (MMs) with effective parameters (EPs), provided that they can be introduced. Up to now, a large variety of retrieval methods has been suggested. In general, these methods are either simple but give wave (or nonlocal) EPs, or they provide material (local) parameters but at the cost of complexity in realization and/or limited applicability. Wave parameters may be sufficient when only the refection/transmission spectra at a fixed incident angle are considered. The universal description of MM properties should be based on material EPs. However, procedures of their retrieval are not fully established yet.

In this contribution, we present a retrieval method which recovers both material and wave parameters. The main advantage of our method is its simple numerical realization. The first part of the method involves the extraction of the dominating (fundamental) Bloch modes from the simulation data of the field distribution in several unit cells. Then, we explicitly perform either volume or surface averaging of the electric and magnetic fields of the dominant forward-propagating Bloch mode over the unit cell. The ratio of the surface averaged fields provides the value of the Bloch impedance and, respectively, enables the retrieval of wave EPs. The volume averaging provides the wave impedance, which is needed for the retrieval of the materials parameters. We call our method the field averaging of the restored Bloch mode (FARBM).

The FARBM method is simple and unambiguous, free of the so-called “branch problem”, which is an issue for the methods based on reflection/transmission properties, and has no limitations on a metamaterial slab thickness. The FARBM method does not require averaging different fields’ components at various surfaces or contours. The retrieval procedure is performed within a single computational cycle, after exporting fields on the unit cells entrance facets or in its volumes directly from Maxwell’s equations solver.

We show that the FARBM method is able to retrieve both material and wave EPs for a wide range of materials, which can be lossy or lossless, dispersive, possess negative permittivity, permeability and refractive index values, including the following examples: (1) homogeneous slab under two cases: lossless and Lorentz dispersion in permittivity and permeability; (2) a set of nanospheres with plasmonic resonances; (3) split cubes metamaterials that possess magnetic resonance and negative permeability; (4) a wire medium with negative permittivity; (5) negative refractive index fishnet structure; and (6) split-cube-in-carcass structure.

Concerning the method constraints, we observe that material EPs that are obtained with the FARBM method for nonlocal MMs (e.g. the fishnet or split cube in carcass) possess double anti-resonances. This is the evidence that the method, which is developed for material (local) effective parameters, cannot be applied to nonlocal MMs with a strong spatial dispersion. This suggests that the FARBM method may be also useful for checking the locality properties of EPs for the MM structures.

8070-07, Session 2

Complex Fourier factorization techniques in calculation of modes of discontinuous optical structures with an arbitrary cross-section

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Fourier-expansion-based theories treating electromagnetic propagation in periodic (or pseudo-periodic) media such as diffraction gratings, waveguides, or photonic crystals have been the subject of considerable development for past several decades. For discontinuous structures the method suffered from poor convergence until the correct Fourier factorization principles were postulated by Lifeng Li. Those rules have been successfully applied to anisotropic or slanted gratings, arbitrary-reliefs, two-dimensional (2D) periodic structures, etc., and are also used for other (nonperiodic) applications. As regards 2D structures, however, considerable troubles appeared in the case of cylindrical elements for which Li’s method was not convenient. For this purpose some authors have modified this method by treating independently the tangential and normal components of fields on the edges of cylindrical elements. However, these approaches always dealt with linear polarizations and thus ignored the fact that the transformation matrix of polarization then became discontinuous at some points of space, which might slow down the convergence of calculations for some input parameters. Here we present our recent advances in Fourier factorization techniques, starting with our complex Fourier factorization (CFF) method applied to 2D-periodic circular elements. Our approach avoids the points of discontinuity of the polarization transformation by employing generally elliptical polarization bases, simply by using complex-valued Jones matrices. We provide a brief description of the theory, demonstrating the technique of calculation of optics in 2D periodic structures as well as photonic band structures. The results of calculations employing the CFF method are compared with the previously used methods of factorization with respect to the convergence properties, exhibiting the considerable improvement of the new method. Then we modify our approach to 2D discontinuous structures with an arbitrary cross-section (including rectangular and more complicated systems). On various numerical examples we demonstrate how our method saves the computer memory and the time of calculations.

8070-08, Session 2

The development of metamaterials basing on the model of multi-phase systems

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(Russian Federation); V. V. Shchennikov, Jr., Institute of Engineering Science (Russian Federation); I. A. Komarovskii, Institute of Metal Physics (Russian Federation)

The recent progress in creation of left-handed materials inaccessible for natural substances shows all-important role of the multi-phase materials in modern technology. In the present work the approach potentially useful for producing of metamaterials with the predicted properties is discussed. The approach is based on interpolation formulas obtained between the rigorously calculated limiting borders, and it allows to calculate the various thermal, electrical, mechanical, etc. properties of multi-phase with ordered inclusions having varying configuration and concentration [1-3]. The model describing the dependence of electronic properties of multi-component heterophase systems on concentration and configurations of inclusions allows to point out the ways for improving of electronic properties (e.g. thermoelectric effectiveness, thermoelectric and thermomagnetic figure of merit, etc.[4]) and also for extending of functional possibilities of such systems.

The examples of application of the above model are given for the analysis of multi-phase states in the vicinity of pressure-induced phase transitions [3]. The program for calculation of different electrical, thermal, mechanical etc. properties of n-phase systems with variety of configuration and concentration of phase inclusions has been created, which may be applicable for development of real metamaterials with the predictable set of properties. The approach offered may be used for optimization of properties and for design of micro devices with improved characteristics.

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8070-09, Session 3

Plasmonic nano-bubble cavity probed by cathodoluminescence

N. X. Fang, Massachusetts Institute of Technology (United States) and Univ. of Illinois at Urbana-Champaign (United States)

In this invited talk, we report the observation of strongly confined local optical mode at the rim of nano-cavity using Cathodoluminescence microscope. Nanoscale cavity with trapped air bubble is generated by focused ion beam exposure and trapped in between Ag and a thin Si layer. High energy electron beam is focused on the structure to induce photon emission. Radiation from the structure is collected while electron beam is scanning over the area in raster mode, forming a high resolution optical image. We observe concentric-ring patterns similar to the Newton's ring. The peak position is highly dependent on the air gap size and the wavelength of light. Theoretical modeling indicates that there are two physical origins. The outer rim peaks up due to increased local density of states originated from plasmonic field confinement in the subwavelength air gap. The inner rings are analogous to conventional Newton's ring which is caused by an interference of light.

8070-10, Session 3

Gold nanostructures using tobacco mosaic viruses for optical metamaterials

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The metamaterials working in a frequency range of visible light need to be composed of nanometer-scaled metal structures. Tobacco mosaic virus (TMV) is a tube-shaped plant virus consisting of a helical single-strand ribonucleic acid (RNA) and surrounding 2130 coat proteins. The virus is 300 nm in length with outer- and inner-diameter of 18 nm and 4 nm, respectively. The virus has been one of the favored bio-template proteins for making nanometer-scaled structures [1, 2]. In this contribution, we used a genetically-modified TMV as a template for making gold nanostructures.

Previously, a peptide named TBP1 has been identified to have an ability to be a nuclear site for metallic crystals [3]. We genetically fused the peptide to the outer-surface of TMV in anticipation of preferred metallization at these sites. The mutant TMV was expressed in a tobacco plant and purified. Potassium chloroaurate was mixed with the mutant TMV in 5% acetic acid solutions, and reduced by sodium borohydride. Transmission electron microscopic (TEM) images show that gold nanoparticles are deposited on the outer-surface of the virus. The diameter of nanoparticles was 4 nm, which is smaller than those deposited on wild-type TMV. Even though it is still difficult to control the size and shape of gold deposited on the mutant virus, genetically-modified TMV is a promising template for construction for optical metamaterials. In the conference, the mechanisms of metal nanoparticle formation will be discussed.

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8070-11, Session 3

Vacuum Rabi splitting and strong coupling dynamics for surface plasmon polaritons and Rhodamine 6G molecules

R. J. Moerland, Aalto Univ. School of Science and Technology (Finland); T. Hakala, Univ. of Jyväskylä (Finland); G. Sharma, A. Vakevainen, Aalto Univ. School of Science and Technology (Finland); J. Toppari, Univ. of Jyväskylä (Finland); A. Kuzyk, Aalto Univ. School of Science and Technology (Finland); M. Pettersson, H. Kunttu, Univ. of Jyväskylä (Finland); P. Törmä, Aalto Univ. School of Science and Technology (Finland)

We report on strong coupling between surface-plasmon polaritons (SPP) and Rhodamine 6G (R6G) molecules, with double vacuum Rabi splitting energies up to 230 and 110 meV. In addition, we demonstrate the emission of all three energy branches of the strongly coupled SPP-exciton hybrid system, revealing features of system dynamics that are not visible in conventional reflectometry. Finally, in analogy to tunable-Q microcavities, we show that the Rabi splitting can be controlled by adjusting the interaction time between waveguided SPPs and R6G deposited on top of the waveguide. The interaction time can be controlled with sub-fs precision by adjusting the length of the R6G area with standard lithography methods.

This is one of the first observations of Rabi splitting with SPP. It is the first one where a molecule with a broad spectrum was used, and the first one where dynamics of the phenomenon was studied. The dynamics was studied in two ways: having several detection settings in the Kretschmann configuration, and by a totally novel way, namely measuring the spectrum of SPP that had been propagating on a waveguide and interacting with molecules for a controllable time. The results were published in: Hakala, T.K., Toppari, J. J., Kuzyk, A., Pettersson, M., Tikkanen, H., Kunttu, H., and Törmä, P., Vacuum Rabi splitting and strong coupling dynamics for surface plasmon polaritons and Rhodamine 6G molecules, Physical Review Letters 103, 053602 (2009).

8070-12, Session 3

Experimental investigation Vaviliv-Cherenkov radiation from metamaterials

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Last years artificially structured composites (metamaterials) are intensively investigated in respect to the negative index of refraction over a band of microwave frequencies. Different structures were studied theoretically and tested experimentally on real photon beams. On the other hand, the electromagnetic field of relativistic particles may be considered as a pseudo-photon field with a good accuracy. In this case we can expect new effects in interaction of the charged relativistic particles with metamaterials. It is interesting to consider the analog of Vavilov-Cherenkov radiation in band of microwave frequencies interaction of the relativistic electrons with artificially structured composites. In this wavelength region the effective electron field may be of macroscopic range, and we can study the Vavilov-Cherenkov radiation for electrons moving close to a target without a direct interaction. In this work we present the results of experimeral investigatins of the Vavilov-Cherenkov radiation for electrons with energy 6.2 MeV mooving close to the target consisting of a conventional multilayer SRR/wire structure. The features of spectral and angular properties of this radiation in millimeter wavelength region were observed and investigated. Due to the large spectral dispersion of this radiation the observed effect may be used in noninvasive electron beam diagnostics as a simple tool for a bunch length measurement.

8070-17, Session 4

Fabrication of corrugated probes for scanning near-field optical microscopy

P. Wróbel, Univ. of Warsaw (Poland); T. J. Antosiewicz, Interdisciplinary Ctr. for Mathematical and Computational Modelling (Poland); A. Libura, G. Nowak, Institute of High Pressure Physics (Poland); T. Wejrzanowski, R. Slesinski, K. Jedrzejewski, Warsaw Univ. of Technology (Poland); T. Szoplik, Univ. of Warsaw (Poland)

Various nanotechnological means of observing or fabricating structures smaller than the wavelength of light have been developed to address diverse needs of research and industry. Some of them deal with concentration of light by transforming propagating waves in isotropic media to surface plasmon-polaritons (SPPs) at metal-dielectric interfaces. Such devices come in many forms, e.g. bare tapered optical fibers, tapered metal-clad fibers with or without an aperture at the end, tapered solid metal cones, laterally tapered plasmonic waveguides and metamaterial nanotips. Applications of light concentrators range from chemical sensors of molecules, to visualization devices, and nanolithographic tools.

In finite-difference time-domain simulations we observed that corrugations of the core-coating interface of scanning near-field optical microscope (SNOM) aperture probes enhance transmittance by more than one order of magnitude due to excitation of plasmons, yielding a theoretical 50% decrease of the aperture diameter [Opt. Express 15, 10920 (2007)].

In this communication we describe a method of fabricating a corrugated scanning near-field optical microscope probe which employs light to plasmon conversion to increase energy throughput. The procedure is a one-step chemical etching scheme, based on the Turner method, of a germanium doped silica fiber with a distributed Bragg reflector (DBR) at the to-be-tapered part. The etch rate of the Ge-doped hydrogenated fiber core is selectively modified by writing the DBR using a UV laser beam passing through a diffraction phase grating. The refractive index contrast introduced by the procedure differentiates diameter etching rates of exposed and unexposed parts of the core by about 100 nm/min at room temperature, as measured from fabricated samples by scanning electron microscopy. The fiber core is 8 microns in diameter and under normal conditions is etched in just under 4 minutes forming grooves up to 140 nm deep. The lattice period is dependent on the Bragg lattice and diffraction efficiency of the phase grating. In a perfect setup the groove lattice should be equal to the DBR lattice. However, for real phase gratings the zero order diffracted light lowers the intensity of every second peak yielding a groove periodicity twice that of the DBR, what is observed in our experiment.

The presented fabrication method is suitable for fabricating plasmonic SNOM probes with enhanced energy throughput.

8070-18, Session 4

Slowing light in all dielectric tapered left-handed waveguide

T. Huang, T. Yen, National Tsing Hua Univ. (Taiwan)

Slowing light has arisen increasing attentions due to its applications for optical switching, optical hard disk and enhanced photon-matter interaction, especially the system utilizing left-handed tapered waveguide (LHWG) to possess either oscillatory mode or surface plasmon polariton (SPP) mode which are the most possible candidate to be commercialized. But both of them suffer from the loss coming from metal to limit the time to trap photons in the LHWG. Hence, we hire highly contrast dielectric metamaterial as LHWG to reduce the ohmic loss from metal and demonstrate slowing light effect. Our results are confirmed by introducing E-field (or H-field) distribution and power flow recording in CST simulation software. In this work, we successfully present slowing light effect by utilizing periodic dielectric cubes metamaterial in experiments. The function of metal to create negative permittivity is replaced by dielectric material which decrease the ohmic loss generated by metal and increase trapping time as much as possible. And one step further, we demonstrate a tapered dielectric waveguide to perform not only slowing light effect at single frequency but also ‘trapped rainbow’ effect for multi-frequency light trapping. The experiments of tapered dielectric waveguide are ongoing.

8070-32, Session 4

Ultrafast and nonlocal effects in plasmonic metamaterials

A. V. Zayats, King’s College London (United Kingdom)

A large number photonic and nanophotonic applications, including negative index engineering, superlensing, optical cloaking and passive and active integrated photonic circuitry rely on plasmonic metamaterials. One promising class of such metamaterials is based on plasmonic nanorod arrays. These consist of metal nanorods (20-60 nm diameter, 40-80 nm spacing between rods, 50-500 nm length) attached to the substrate with their axes aligned perpendicularly to it. The nanorods can be free standing or immersed in dielectric, e.g., polymer matrix. They are inexpensive to fabricate over large areas.

Optical properties of the arrays are determined by strong interaction between plasmon resonances of the individual nanorods and are due to collective plasmonic response of the closely spaced nanorods in the array. The resonant frequency of such collective plasmonic excitations and spatial variation of the associated electromagnetic field distribution can be designed by modifying the nanorod array parameters: size of the nanorods, their separation, permittivity of the metal and embedding dielectric matrix. Thus the opportunity exists to control the optical response of the metamaterial and tune their optical properties using applied electric field or all-optically with appropriately suited nonlinear materials as a matrix.

In this talk we will present our recent results on ultrafast all-optical switching of optical transmission/absorption of nanorod metamaterials in sub-picosecond regime, governed by the collective plasmonic response of the nanorods. We will also demonstrate that optical properties of low-loss nanorod materials in the spectral range close to the epsilon-near-zero regime is strongly affected by nonlocal optical response. The evidence of excitation of additional wave in such systems has been recently demonstrated.

Both additional waves and ultrafast optical response allow development of new applications for controlling light with metamaterials. In particular, additional waves not only change the optical response of the metamaterial, but also form a new information channel that may be beneficial for future nanoscale datacom applications. Ultrafast nonlinear response provides an opportunity to design tuneable optical metamaterial devices (e.g., superlens) as well as modulation and switching of optical signals in subwavelength-thick mesoscopic devices and metamaterial waveguides.

8070-33, Session 4

Optimization of transmission and focusing properties of plasmonic nanolenses

P. Wróbel, Univ. of Warsaw (Poland); T. J. Antosiewicz, Interdisciplinary Ctr. for Mathematical and Computational Modelling (Poland); T. Szoplik, Univ. of Warsaw (Poland)

Plasmonic focusing devices are different from dielectric transparent refractive lenses in that transmission and light concentration are governed by consecutive photon-plasmon and plasmon-photon couplings. Their properties depend on various geometrical parameters like lattice constant or lack thereof like in Fresnel lenses, groove depth, groove or slit width, metal thickness and type. Depending on the illuminating wavelength used, the lens may act as a far-field focusing device, like considered by us in this note, or as an on-axis plasmon amplifier.

We consider two kinds of plasmonic nanolenses which focus a radially polarized Laguerre-Gauss beam into a subwavelength, diffraction limited spot. The first one is a free-standing opaque metal layer with concentric grooves on both sides [Phys. Rev. Lett. 102, 183902 (2009)]. The second lens has slits instead of grooves and, for support, is integrated with a dielectric matrix. Subwavelength focusing is observed due to constructive interference of the longitudinal component of the electric field of far-field radiation of SPPs efficiently generated on the back side the lens.

We investigate transmission and focusing properties of the considered metal structures. Choice of appropriate metal e.g. silver, gold, copper or aluminum strongly affects transmission, while geometrical parameters of the surface structure determine efficient photon-plasmon coupling and plasmon scattering phenomena, thus influencing both transmission and focusing. Finally, the right choice of the dielectric function of surrounding media gives another degree of freedom to fulfill momentum matching condition for resonant photon-plasmon interaction. Taking into account the above mentioned parameters, we show an optimization procedure leading to optimum transmission, focal spot and focal length of considered plasmonic nanodevices. Transmission up to 70%, focal lengths in the range 1-5 wavelengths and full-width at half-maximum down to 0.42l are achievable.

8070-34, Session 4

Generation of nondiffracting subwavelength-beams in finite metal-dielectric structures

C. J. Zapata-Rodriguez, D. Pastor, Univ. de València (Spain); J. J. Miret Mari, M. T. Caballero Caballero, V. Camps Sanchis, Univ. de Alicante (Spain)

The term nondiffracting beam (NDB) embraces electromagnetic fields of a transverse intensity profile remaining unchanged in free-space propagation. The most familiar NDB is the Bessel beam, which has been successfully used in optical manipulation, biophotonics, optical microlithography, and optical coherence tomography. This sort of solution of the wave equation may be found in stratified media. However, out-of-plane excitation cannot support an invariant propagation of beams with a Bessel profile. Nevertheless, we always can generate a NDB superposing a suitable set of plane waves (PWs) all having a wavevector (WV) which gives the characteristic propagation constant β if it is projected onto the propagation axis. If, additionally, a phase matching condition is established we will achieve high transverse localization.

In this contribution we identify nano-structured devices sustaining out-of-plane NDBs with near-grazing propagation and transverse beam sizes clearly surpassing the diffraction limit of half a wavelength. This type of device consists of a planar multilayer metal-dielectric (MD) structure with a finite number of layers deposited on a solid substrate. The metallic and dielectric media are silver and fused silica respectively. Realistic material losses are also considered.

The beam is launched from the substrate with a set of monochromatic PWs all having the same on-axis WV (β). In fact, we construct the NDB superposing only those PWs that are resonantly transmitted. Specifically, the system presents a series of transmission bands, which coincide with allowed bands of the infinite 1D MD. High transmission resonances appear within these bands, associated with the excitation of bound modes of the structure. We perform an optimization process concerning the layers width as free parameters in order to reach the most efficient and uniformly-transmitted resonances. Finally, the value of β and the focal placement are initially arbitrary and can be chosen according to the potential application. Possible applications include optical trapping and guiding of micro- and nano-size objects and femtosecond laser submicrochannel machining in glass.

In a numerical simulation we have selected β equal to the wave number in vacuum and a focal point placed on the upper metal-dielectric interface. The widths of Ag and fused silica films are 12.5 nm and 80 nm respectively, the number of films of each material is 10 and the vacuum wavelength is 550 nm. We perform a homogeneous superposition of 20 phase-matched PWs leading to a NDB with an anisotropic beam size of 80 nm and 20 nm along both transverse directions.

8070-37, Poster Session

Angle-dependent excitation of surface plasmon polaritons in gold nanwires embedded in alumina

O. Yeshchenko, I. Dmitruk, National Taras Shevchenko Univ. of Kyiv (Ukraine); Y. Barnakov, Norfolk State Univ. (United States)

We studied the extinction spectra of parallel gold nanowires (diameter - 27 nm, length - 9 $mu $m) in alumina matrix, where axes of the parallel nanowires are perpendicular to the surface of the sample. Two bands (marked as T and L) were observed in the spectra. T-band originates from the excitation of the localized transversal surface plasmons in the nanowire, and L-one - from the excitation of longitudinal surface plasmon polaritons propagating in the nanowire. The transversal T-band was observed in any polarization of the exciting light. Its total intensity is described by the common expression $I_{T} propto (sin phi + cos theta cos phi) ^{2}$, where $phi $ is the polarization angle and $theta $ is the angle between the wave-vector of exciting light beam and the axis of the nanowire. No dependences of its spectral position and bandwidth on $phi $ and $theta $ were observed. L-band is absent in S-polarization ($phi = 90 ^{0}$) and has highest intensity in P-polarization ($phi = 0$). It is remarkable that all the spectral characteristics of L-band are characterized by strong non-monotonic dependences on the angle $theta $ in P-polarization with extremes at $theta approx 35^{0}$. At $theta approx 35^{0}$ the intensity of L-band has maximum, its wavelength has maximum, and the bandwidth has minimum. We showed that such angle dependences are caused by the excitation in gold nanowires of the longitudinal surface plasmon polaritons (SPPs) that are the eigenmodes of the nanowire that acts as plasmonic cavity. The theoretical calculations showed that efficiency of the excitation of these surface polariton modes is maximal at $theta = 35^{0}$. At this angle the axial modes are excited, and the unaxial modes are excited at smaller and higher angles $theta $. The axial SPP modes have the lowest frequency and lowest damping at the propagation in the nanowire, and the unaxial modes have the higher frequencies and higher damping. These theoretical considerations are in full agreement with experimental dependences of L-band spectral characteristics on the incidence angle $theta $.

8070-39, Poster Session

Flat photonic lattices for near-field imaging with enhanced depth of field

C. J. Zapata-Rodriguez, D. Pastor, Univ. de València (Spain); J. J. Miret, Univ. de Alicante (Spain)

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Near-field flat lenses are photonic elements with the ability of forming real images with subwavelength resolution. This phenomenon is attributed to the predominant contribution of evanescent waves in the imaging process, which comes out naturally under the excitation of surface resonances. Thus evanescent waves are amplified in bulk media with negative index of refraction to compensate the exponential attenuation observed in free-space propagation. However, wave amplification is strongly constrained by material losses limiting the resolution power of the imaging-forming system.

Dissipation in bulk metamaterials may be counterbalanced by dividing the nanoslab into equidistant thin films. Harmonizing the widths of each fragment and the adjacent interspaces leads to the formation of real intermediate images located at planes neighboring the metamaterial-dielectric interfaces, which alleviates the evanescent-field amplification. As a consequence, absorption effects in left-handed media are palliated and the high-frequency transparency window broadens substantially. In an inherent manner the limit of resolution falls off by far.

Nonetheless there is a price to pay for using such a multilayer scheme. The distance between the object plane and the input surface of the photonic device also decreases considerably. The stratified setup discloses practical impediments in order to produce real images from scatterers placed out of focus, and the depth of field is reduced accordantly. In this communication we propose some heterogeneous designs based on the control of the widths of each superlensing unit as a tradeoff between reduced limit of resolution and enhanced depth of field. As a consequence the optical system may conserve a high degree of 3D imaging performance simultaneously as we proceed to increase its resolution power.

8070-40, Poster Session

Modeling of metamaterials: a globular protein as a metamaterial prototype for electromagnetic-acoustic energy conversion at low temperatures

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The investigation is devoted to give proof to the simple idea, that a globular protein is a molecular machine. This machine effectively converts electromagnetic energy of thermal equilibrium radiation to energy of acoustic oscillations associated with low-temperature equilibrium fluctuations of protein structure.

The laws of thermal equilibrium radiation , the activation process model and photon-to-phonon transformation mechanism in solid state are used to prove this idea.

The absorbing ability of a globule is calculated for myoglobin and beta-hemoglobin macromolecules. It is shown, that up to 36 - 37 % of electromagnetic energy of thermal equilibrium radiation is conversed to energy of the phonon bath. Then the bath's energy is used to enable low-temperature equilibrium fluctuations of a globule. Thus, it is proved, that protein macromolecule is an acoustic resonator capable to store energy for structural transformations.

So, a globular protein can be used as a metamaterial prototype for electromagnetic-acoustic energy conversion at low temperatures.

8070-41, Poster Session

Metamaterial coatings for subwavelength-resolution imaging

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Coating thin films are widely applied on optical elements in order to minimize reflection losses. Making one of these layers of a material exhibiting negative permittivity and permeability, localized scatterers placed nearby may be imaged behind. This device is also known as the asymmetric flat lens. Such an imaging system is mechanically much more stable than a standard nanoslab sustained in free-space since it is commonly deposited on a solid substrate. Interestingly the index of refraction in the image space may be conveniently chosen to be higher than that corresponding to the medium surrounding the object. As a consequence, some evanescent waves launched by the source become of homogeneous nature after passing through the lens, leading to the formation of a far-field image with subwavelength resolution.

The main disadvantage of negative-refractive-index (NRI) coatings consists of providing images with imperfections derived from geometrical aberrations and multiple-scattering losses. For silver superlenses, it is well-known that amplification of evanescent waves sustained by surface waves is more favourable if the real part of the dielectric constant of the metal and the substrate matches except for its sign. In this communication the effects of aberrations and reflection losses are thoroughly investigated in asymmetric superlenses made of metamaterials with NRI.

Let us present some preliminary results. In the non-paraxial regime, the spherical aberration (SA) may be compensated if the NRI of the film is comparable with the index of refraction in the object space. Additionally, compensation of SA is satisfied provided the internal paraxial image lies approximately in the middle of the slab. We point out that such a situation might be unfavourable for extreme-subwavelength resolution imaging. Nevertheless far-field imaging clearly recovers subwavelength information transmitted within a prescribed spectral band associated with evanescent waves launched by the object.

8070-42, Poster Session

Capabilities of NSOM lithography using metal coated fiber tip for 2D photonic structures fabrication

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This contribution presents possibilities of the near-field scanning optical microscope (NSOM) lithography using metal coated fiber tip. The NSOM lithography that has several advantages over the other radiation based nanolithography techniques. Patterning of structures is done through a direct writing process, which is performed by the optical near-field produced at the tip of a fiber probe. Thus, the main advantage is the fabrication of structures with size below diffraction limit of the light source.

In this contribution, the NSOM lithography is used for fabrication of two-dimensional (2D) photonic structures. The non-contact mode of the NSOM lithography is performed, where the fiber probe realizes the in-plane movement over the sample surface without touching the surface. As the fiber probe, a metal coated tapered optical fiber is used. In combination with three-dimensional nanoposition stage, fabrication of 2D photonic structures with either regular or irregular arrangement in a thin photoresist film deposited on GaAs substrate is shown. Characteristics of prepared photonic structures are demonstrated by atomic force microscope analysis.

As the quality of prepared photonic structures strongly depends on the metal coated fiber tip parameters, a detailed analysis of the used fiber probe is realized. The optical field irradiated from the fiber probe is examined by NSOM in collection mode using another fiber tip, which works as a detector. Optical field scans are taken in a plane perpendicular to the fiber probe axe in different distances from the fiber probe. By this method, both the far-field and the near-field characteristics of the irradiated optical field are obtained. From this near- and far-field analysis, shape and size of the aperture, parameters of the near-field region or the divergence angle in the far-field can be estimated.

8070-43, Poster Session

Electrical and optical properties of GaAs/AlGaAs photodiodes with integrated 2D pattern in the surface

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Skriniarova, Slovak Univ. of Technology (Slovakia); I. Kubicova, I. Martincek, Univ. of Zilina (Slovakia); J. Novak, Institute of Electrical Engineering (Slovakia)

New applications in photonics and optoelectronics are focused on the exploitation of periodic structures in the case of submicrometer period known as photonic structures. One of the simplest way, how to obtain the periodic microstructures with two-dimensional (2D) geometry is interference lithography based on a double-exposure process using two-beam interference optical field. In this way, the interference lithography can produce periodic microstructures in large areas. These periodic structures patterned in thin photoresist layer can be employed as a mask for patterning of III-V semiconductor surfaces, what may be attractive for optoelectronic and photonic applications.

Using the interference lithography based on the two beam interference method, the 2D periodic structures with square symmetry were prepared in different III-V compounds surface layers. This technique was applied to the surface patterning of a GaAs-based photodiode, where the 2D periodic pattern in the surface is integrated. The active region of the photodiode includes a GaAs/AlGaAs triple quantum well. Interference lithography was used for preparation of 2D pattern in deposited thin photoresist layer and then transferred in the upper diode layer using reactive ion etching.

The final structure pattern was analyzed by the atomic force microscope and scanning electron microscope. Such prepared photodiode with 2D patterned microstructure in the surface was investigated by electrical and optical measurements. I-V and spectral measurements using a grating monochromator confirmed the influence of the 2D periodic structure on the photocurrent response.

Finally, the effect of nanoparticles on optical characteristics was studied. Nanoparticles of CdTe and CdSe/ZnS were embedded into the 2D microstructure pattern in the photodiode surface. The enhanced light absorption was documented from the I-V measurements and from the photocurrent spectra.

8070-44, Poster Session

GaAs/AlGaAs light emitting diode with 2D photonic structure in the surface

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Integration of photonic crystal (PhC) in light emitting diodes (LED) have attracted much attention because of the improvement of optical properties as light extraction enhancement, polarization and directional patterns. One of the simplest way, how to obtain the planar photonic crystal with two-dimensional (2D) geometry is the interference lithography based on a double-exposure process using two-beam interference optical field. In this way, the interference lithography can produce PhC structures in large areas with submicrometer period. Using the interference lithography based on two beam interference method, the 2D photonic structures with square and triangular symmetries were prepared in the III-V compounds surface layers.

In this paper, effect of 2D photonic pattern on the emission properties of the GaAs/AlGaAs based LED is demonstrated. The interference lithography was employed to surface patterning of the GaAs/AlGaAs-based LED. The active region of the LED includes a GaAs/AlGaAs triple quantum well emitting at 850 nm. Interference lithography was used for preparation of 2D pattern in deposited thin photoresist layer and this photoresist pattern was transferred in the upper diode layer using reactive ion etching.

The prepared PhC structure pattern in the LED surface was analyzed by atomic force microscope and scanning electron microscope. Such prepared LED with 2D patterned photonic structure was then investigated by electrical and optical measurements. The near-field scanning optical microscope was used for characterization of near- and far-field pattern. Effect of different periods and symmetries of 2D photonic structure on emission properties in a near- and far-field region was investigated. 2D PhC LED shows enhanced extraction efficiency due to the effective extraction of guiding modes. In the near- and far-field pattern, the 2D PhC structure documents the enhanced light extraction from the patterned air holes in the LED surface.

8070-45, Poster Session

Model for the effective medium approximation of nanostructured layers with the account of interparticle interactions

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Existed models of the effective medium approximation can not be directly applied for nanostructured layers like nanoparticles on a surface for two reasons:

- they do not account intrinsically anisotropic environment for particles in layers;

- they don not account direct interparticle interaction.

In contrary to the approximation of nanocomposite properties in the case of bulk, the geometrical anisotropy of 2D layers results in the line splitting for transversal and longitudinal polarizations. At the same time the account of direct interparticle interaction reflects in the shift of plasmon resonances with the particle concentration, which is absent in the standard Mazwell-Garnett model.

On the base of self-consisted approach with the use of Green functions we developed the model of the optical response of the layer of nanoparticles randomly distributed on the surface [1]. In contrary to the standard models of the effective medium approximation the direct electromagnetic interaction between the particles was taken into account in this model by the Lipman-Shwinger [2] equation. The solution of this equation in the Fourier space in the so-called k-z approximation allows to determine the average polarizability of the layer on the base of parameters of constituting particles and their concentration. Such an analogue of the effective medium approximation intrinsically includes the geometrical anisotropy of the layer as well as interparticle interactions demonstrating both the anisotropy in the optical parameters and the dependence of the resonance of the system on the particle concentration. Such polarizability can be used in calculations of different optical response of systems with nanostructured layers.

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8070-47, Poster Session

Optical study of nanoporous C-Pd thin films

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The potential possibility to use and control photons in a manner analogous to control of electrons in solids has inspired many research groups to look for new materials with unusual optical properties. The photonic material is translucent at all wavelengths except at the energies within the gap. In the sub-wavelength hole arrays samples, the material plays an active roles (through the plasmons) and it is opaque at all wavelengths except those for which coupling occurs. Findings novel materials with optical features are very interesting from both fundamental and technological points of view and will inspire designs new photonic devices. A nanoporous carbon - metal structures can be the example of such materials due to their promising features e.g. the tunability of the electronic structure. The electrical and optical properties of the nanoporous materials of this type are not yet fully understood.

In recent years new nanocomposites containing palladium and carbon nanostructures have been prepared in Tele- and Radio Research Institute. Samples were obtained using two step PVD/CVD method and have about 300nm in thickness and contain from 1 - 20% wt. of Pd. The optical features of materials were investigated using optical transmission spectroscopy (OS), Photoluminescence (PL) and Raman Spectroscopy (RS) techniques, both after first (PVD) and second step

(CVD) of technological process. Raman spectra shows existence of fullerite-like structure in PVD samples and NC-graphite (disordered) structure in CVD samples. Based on UV-VIS-NIR spectra, value of the extinction coefficient k for our CVD samples was estimated about 0.2-0.3 in NIR region. It is about 4 times less than for other samples of disordered carbon. Optical spectra of PVD samples are probably connected with C60 fulleren existence. Additionally, no distinct luminescence emission was observed for studied samples. We can conclude that low value of extinction coefficient can be connected with heterogeneity of structure (presence of Pd metal grains and pores). Theoretical analysis of the results and further research would also be useful for better understanding this unusual optical properties of nanoporous carbon - metal composite thin films.

Acknowledgements

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8070-19, Session 5

Metamaterial based enhanced transmission from deep subwavelength apertures

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We obtained enhanced transmission of electromagnetic waves through a single subwavelength aperture by making use of the resonance behavior of a split ring resonator (SRR). We experimentally observed as high as 70,000 times metamaterial based transmission enhancement factors from our samples.

8070-20, Session 5

Nanoscale double asymmetric split ring resonators

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Metamaterials based on nano-scale metallic split ring resonators (SRRs) can be used to produce resonant responses in the visible and mid-infrared wavelength range.However, the quality factor of resonance associated with metamaterials is usually low due to the strong coupling of the SRRs with free space and that result in radiation losses. This lossy nature of SRRs and its broad resonant response makes it difficult for practical and efficient implementation of metamaterials in applications such as optical sensors. A high quality factor is desirable if the structures are used as sensors, because a shift in a sharp peak is easier to detect than a shift in a gentle slope. It has been shown in a few theoretical and experimental studies that it is possible to obtain higher quality factor resonance in metamaterials by introducing certain asymmetries into the SRR geometry using asymmetric split ring resonators (A-SRRs).

Nano-antenna arrays of gold-based asymmetric split-ring resonators (A-SRRs) show strong resonance effects in both the microwave and infrared regimes. The strongly resonant response of A-SRRs have been utilised for resonant optical detection of very thin films of organic compounds. The resonant response of an A-SRR can be further augmented by including another set of concentric but asymmetric arcs encircling it - in a double asymmetric split-ring resonator (DA-SRR) structure. In a DA-SRR there are two sets of A-SRRs (inner and outer) that are concentric to one another. The DA-SRR consists of arcs with four different lengths (as compared to two arcs of an A-SRR) that share the same centre-of-curvature. All four arcs act as individual resonators and produce distinct plasmonic resonances - but their overall response is modified by their proximity to one-another, resulting in steep response slopes. In an A-SRR the two asymmetric arcs interact to produce sharp resonances separated by a reflection dip region that was identified as the trapped mode by Fedetov et al. . The trapped mode is characterised by a substantial increase in the resonant absorption, corresponding to minima in both reflection and transmission. The greater number of arcs for the case of the DA-SRR enables a greater number of the trapped modes, for which there is a substantial amount of absorption, corresponding to energy stored (and dissipated) in the four coupled arcs.

8070-21, Session 5

Fabrication and characterisation of metallised woodpile structures

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The request for fabrication and characterization 3D structures possessing desired functionalities has boosted in the last years. Together with the advance in metamaterials research, new techniques have been developed for addressing the need of such structures.

The so-called woodpile structures (WpSs) have a great potential in nanophotonics exhibiting broad functionality and controlled adjustment of their behaviour. Due to their 3D tunability, WpSs can be used as superprisms [1], 3D photonic crystals with complete bandgaps [2] and even invisibility cloaks [3]. In this paper we present results in fabrication as well as in the characterisation of such metal-coated devices.

The fabrication of a WpS can be divided into several branches. On one side, the layer-by-layer approach [1, 4] allows obtaining very high resolution but the fabrication process is long and complex. The other mainly used technique is the two photon polymerisation [5]. Due to its high versatility, we opted for this technique in our approach. To increase the functionality of our structures, we developed an electroless based technique for depositing thin layers of silver on 3D structures [6]. Although there are other techniques for depositing metals on 3D structures, e.g. plasma enhanced chemical vapour deposition [7, 8] or electroplating [9], they require huge optimisation efforts due to the multiple-parameter space or conductive substrates thus limiting the covering possibilities. Also silver is, up to now, the best metal suited for optical needs, but its deposition with controlled characteristics is far from trivial.

The characterisation of WpSs is generally based on measurements and simulations of the bulk, while the border effects are usually ignored. By measuring the transmission characteristics at the edge of these structures we show pronounced differences with respect to the bulk. For example, the transmission at the border of the structure shows peculiar characteristics like enhanced transmission spectra at different wavelengths and in different directions. These effects should be taken into consideration when designing structures to be used in real-life applications with tightly focused light beams.

We present here both the silver deposition technique and transmission/reflection results in the bulk as well as close to the edges of the structures.

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8070-22, Session 5

Analysis of subwavelength-patterned plasmonic structures

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Today's photonic structures often try to effectively incorporate surface plasmons-polaritons (SPP), especially due to their unique properties, connected with the subwavelength region confinement. However, together with this exceptional SPP surface wave localization, the inherent losses of such SPP are always present, hence interposing serious trade-off design strategies for successful plasmonic devices. Apart form already well-used simple metal-dielectric surfaces, nowadays, a great research effort is devoted to understanding and exploitation of more complicated structures incorporating some type of subwavelength patterning. This work is thus dedicated to the analysis of transport transmission / reflection properties within subwavelength-patterned plasmonic structures, both in one-dimensional (1D) and two-dimensional (2D) arrangement. Approximate approaches, based on either effective medium theory and / or microscopic modal model, are applied and effectively compared with rigorous numerical electromagnetic analysis. As the numerical modelling tools, our efficient frequency-domain codes based on the Fourier modal expansions (periodic and aperiodic rigorous coupled wave analysis and bi-directional mode expansion and propagation algorithm, both implementing the so-called "proper Fourier factorization" rules and adaptive spatial resolution technique) have been applied, together with the finite difference time domain technique. Hence, the analysis of several types of subwavelength-patterned plasmonic structures is presented, starting with 1D nanostructured metal-dielectric surfaces, and continuing with 2D subwavelength-modulated structures, as e.g. 2D nanohole / nanopillar arrays, where also such effects as local field enhancement and extraordinary optical transmission are consider. Finally, a possibility of magnetic permeability modulation in one of the surrounding surface layers, in connection to possible metamaterial properties, is considered.

8070-23, Session 6

Multipole model for metamaterials with gain: from nano-laser to quantum metamaterials

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Metamaterials are composites consisting of artificial metaatoms/ metamolecules with typical sizes less than the respective wavelengths [1]. By means of a spatial shaping of the metaatoms and their positioning inside the host matrix, averaged dispersion properties of the metamaterials can be tuned allowing new effects and opening up applications, inaccessible with natural materials. A key point of the metamaterials, which differs them principally from the natural one (at least in a visible wavelength region) is a magnetic response on an external electric field [2, 3].

In this work we summarize the multipole expansion approach developed in [4] in order to describe analytically linear and nonlinear optical properties of metamaterials. We show that especially the consideration of electric quadrupole multipoles (not only the magnetic dipole one) is required by basic principles and provides the possibility to adequately analyse an effective magnetic material response.

In order to validate our model, we applied the formalism for the split-ring resonator and the cut-wire structure. In principle, the formalism is not restricted by any special metaatom geometry and only the intrinsic electron dynamics in the respective metaatom must be known.

The next interesting feature of our formalism is the possibility to treat intrinsic multipole induced nonlinear effects [5]. The second order nonlinear effects (e.g. second harmonic generation) for metaatoms are well described by the presented model. Finally our theoretical observations support the experimental results and the embedded discussion on the origin of the nonlinearity published recently [6].

Recently the model has been extended on the case of metamaterials with gain. In frameworks of the same model the regular dynamics (transient dynamics and stabilized generation) and stochastic properties (linewidth of generation) of a nano laser have been described. An expression for the linewidth above the threshold, obtained using the model, is applied for any lasers with arbitrary relations between relaxation times of an active media and a resonator (for example, the expression is reduced to the known Schawlow-Townes one for the case of high-Q resonators).

The model also allows us to consider quantum metamaterials, where QDs are suggested to be used instead of metallic nano resonators. By pumping of the appropriately positioned QDs a magnetic response without optical losses can be obtained.

Finally, propagation of electromagnetic waves inside the metamaterials with QDs has been investigated, and dependence of a magnetic response on the gain has been analysed.

In conclusion, we present a self consistent, analytical approach to characterize passive and active metamaterials. Since we observe a nice quantitative agreement with rigorous simulations we regard this analytical tool as a potential routine to support the actual research on metamaterials and to make the observed effects reducible to an intuitive and well known physical extend.

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8070-24, Session 6

Optical properties of metamaterials based on asymmetric double-wire structures

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In our work we performed theoretical and experimental investigations of the influence of a unit cell asymmetry on the magnetic properties of a MM consisting of double-wire structures. The double-wire system is one of the favorite configurations of metaatoms owing to its rather simple geometry benefiting its experimental realization. In the considered system of double-wires the asymmetry was introduced by tuning of the wire lengths.

Theoretical analysis of the system was done using the multipole model from [1] extended to the case of asymmetric wires. The approach proposed in [1] is based on a homogenization procedure accepted in the theory of electrodynamics of continuous media. The theoretical model from [1] allowed us to connect the geometrical asymmetry of the structure with the macroscopic effective parameters (an effective dielectric permittivity and an effective magnetic permeability). Numerical simulations were done by FMM; spectroscopic measurements were performed to characterize experimental samples produced by electron-beam lithography.

Our investigation has shown that the magnitude of the magnetic moment and the phase shift relative to the magnetic field depends strongly on the configuration of the system. In general, the dynamics of the system is dominated by the larger wire, where the plasmon oscillations follow the external electric field. This defines the orientation of the effective current in the system of the coupled wires. In a system where the wire on the top is longer than the wire on the bottom, the magnetic moment is strong and has a phase shift of pi with respect to the magnetic field of the illuminating wave. This leads to a decrease of the effective magnetic permeability. In the configuration where the wire on the top is shorter than the one on the bottom, the magnetic moment decreases and oscillates in phase with the magnetic field; the corresponding effective magnetic permeability grows. The obtained results correlate with the ones presented in [2], where a set of asymmetric nano-discs was considered. However, the implementation of the analytical model [1] allowed us to connect the geometrical asymmetry of the structure with the macroscopic effective parameters and facilitate understanding of the internal dynamics of the system.

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8070-25, Session 6

Monte Carlo study of cloaking effects in nanosphere-doped liquid crystal metamaterial

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Recently [1,2] we have discussed the possibility of obtaining large values of local gradients of refractive index in nanosphere-doped liquid crystal (NDLC) metamaterial at infrared frequencies. The director axis orientation and the resultant refractive index distribution are spatially inhomogeneous and can by effectively controlled by electric field, anchoring forces and temperature.

Those tuning factors can be used to design such spatial modulation of refractive index inside NDLC cell containing an object, which leads to cloaking effect, i.e. "invisibility" of the object in some interval of wavelengths.

In this study we work out the Monte Carlo design procedures which tune the anchoring forces and electric field parameters in NDLC system to obtain the effect of cloaking.

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8070-26, Session 6

Equivalent circuit model of single circular open-ring resonators

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In this paper, we present a simple and accurate LC-model of circular open-ring resonators (ORR). The model allows estimating the resonant frequency of the structure from the geometric parameters. It also helps to analyze the behviour of ORR. The model is verified numerically and experimentally in mmwave frequency range with a normal incidence illumination. Moreover, the effect of the geometric parameters has been also studied. The results are very motivating and a good agreement is obtained.

This paper is an attempt to provide an analytical model for the LC resonance of single ORR arrays. The effect of the substrate on the capacitance has been taken into consideration. Besides, the mutual inductance between the ring and its nieghbours is calculated. The retrieved data from the proposed model for several samples are compared with both the experimental and simulation results. Furthermore, the limitations of the model have been analyzed and discussed.

8070-27, Session 6

Invisibility cloaks, superlenses and optical remote scattering

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In recent years, transform optics has become a very active new field. It has been popularized through the idea of J.B. Pendry that an invisibility cloak can be designed by transforming space and considering the corresponding equivalent material properties. Indeed, it is a deep property of the Maxwell's equations that they are purely topological (when written in the proper formalism) and that all the metric aspects can be encapsulated in the electromagnetic material properties. A direct consequence is that any continuous transformation of space can be encoded in an equivalent permittivity and permeability. In this paper, we discuss the meaning of tranform optics to show how global quantities defined by geometric integrals are in fact left invariant by the transformation.

Extending this principle beyond continuous transformations allows to design exotic optical devices such as the invisibility cloak. Another example of transform optics devices are the superlenses: even if these devices were proposed a few years before the rise of transform optics, they are nicely interpreted as corresponding to a folding of the space on itself. It has been suggested that such devices allow a kind of ``remote action" of the scatterers making possible things such as immaterial waveguides called ``invisible tunnels". In this paper, we investigate numerically (using finite element modelling) the behaviour of invisibility cloaks and cylindrical superlenses to show some of their amazing possibilities but also to define some of their limitations. For instance, we study the following case : a cylindrical superlens is designed by radially folding the empty space on itself and do not perturbate the cylindrical waves emitted by a nearby wire antenna (but for the attenuation due to the dissipation introduced in the superlens permittivity in order to avoid the anomalous resonances). The antenna has an image inside the superlens (the negative refraction index coating) and inside the central part of the device (the magnified region). Then, a small perfectly conducting deflector is introduced in the device and acts on the image of the antenna in the central part of the device and forces the waves to propagate only to the right. This can also be interpreted as if the small deflector, magnified by the superlens, has a four time larger image acting on the original antenna.

8070-28, Session 7

Passive and active plasmonic nanoarray devices

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Metal nanoparticle arrays offer the possibility to considerably surpass the optical field confinement of silicon waveguides, the modal width of nanoparticle array waveguides at resonant operation being quite independent of wavelength and approximately three times the particle radius. This could allow denser lateral packing of waveguides as well as shorter resonators, filters and switches. Although a main problem for many albeit not all applications is the optical loss associated with such high confinement metal-based metamaterials.

Two adjacent parallel arrays of metal nanoparticles constitute a directional coupler. Such couplers form the basis of generic types of integrated photonics devices. The coupling length, filtering and switching characteristics are analyzed. We use a hybrid finite-element-method and multi-level fast-multipole-algorithm (FEM/MLFMA) to simulate the structure in the frequency domain with 3D resolution of the particles. The arrays analyzed consist of 50-nm diameter metal particles, where the particle permittivity corresponds to lossless silver to facilitate the analysis, and in anticipation of possible future breakthroughs in reducing the losses. Extremely short coupling lengths, e.g. 490 nm for an array spacing of 90 nm, are obtained, about three orders of magnitude shorter than in conventional couplers based on materials like silica or lithium niobate. A 2.4-nm filter bandwidth is obtained for a 3- m long coupler, indeed very good data for an integrated optics filter. Switching is effected by phase mismatching the waveguides, indicating switch energies in the fJ range.

Estimates of losses in passive metal nanoparticle arrays are quite widely differing in the literature. We perform a systematic study of losses in Ag nanoparticle arrays as determined by group velocity and photon lifetime, and e.g. estimate that for longitudinal waves losses below 10 dB/ m are feasible. This loss is tractable for single devices such as a 0.5 m long modulator.

Longer propagation lengths in plasmonic structures can be achieved by adding gain material. Simulations show that silver clad colloidal quantum dots can constitute a composite-nanoparticle array waveguide with high confinement and vanishing net loss upon pumping [1]. For systems based on loss-compensated operation, propagation lengths and thus system chip sizes will be limited by the build-up of spontaneous emission [2]. E.g. at a compensated loss of 1 m-1 and a signal bandwidth of 10 GHz the propagation length will be ~4 m for a 10-dB signal-to-noise ratio [2], allowing for a small number of individual components, but not large systems.

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[2] L. Thylen, P. Holmström, A. Bratkovsky, J. Li, and S.-Y. Wang, IEEE J. Quantum Electron. 46, 518 (2010).

8070-29, Session 7

Effects of shape, size and orientation on plasmonic coupling in an asymmetric nanoparticle dimer

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The spectral signature of a metal nanopartilce smaller than a wavelength of light is dominated by its dipole Plasmon Resonance (PR), which depends on the nanoparticle material, the dielectric medium in which the particle is embedded, its shape and its size. By changing these parameters one may tune the PR wavelength of a single metal nanoparticle, but when two particles come close to each other, their near-fields overlap and additional possibilities to manipulate by their optical response occur.

It has been seen previously that dimers of equivalent plasmonic nanoparticles (homodimers) show only a bonding mode that is red-shifted with respect to the single particle plasmon mode if the incident light is polarized along the inter-particle axis (longitudinal polarization). They show only an antibonding mode that is blue-shifted if the light is polarized perpendicular to the interparticle axis (transverse polarization). However in most plasmonic applications such symmetry is not present and thus dimers are expected to support both bonding and antibonding plasmon modes.

In this work we consider the plasmon coupling in nanoparticle dimer assemblies, including heterodimer structures with the size asymmetry, the shape asymmetry, and the orientation asymmetry.

The Multiple Multipole Programme (MMP) in conjunctions with the spectral Boundary Integral Equation (BIE) method is used to study the effects of asymmetry numerically on coupling induced optical properties of heterodimers. These numerical algorithms provide the essential flexibility for the calculation of extinction, scattering and absorption characteristics when the incident light orientation and the inter-particle distance are systematically varied.

The presented study provides a solid basis for systematic tuning of the heterodimer resonant wavelengths with a control of resonantly-enhanced absorption and scattering. This is the first step toward the detailed consideration of coupling induced properties of nanoparticles in complex assemblies leading to an improved nanoparticle assembly based nanosensing and plasmonic waveguiding.

8070-30, Session 7

A high-transmission dualband terahertz bandpass filter by exciting multiresonance of metamaterials

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Recently, metamaterials have attracted much attention due to the noble electric or magnetic properties, which are characterized from their unique structure. Such artificial media possess more freedom from their excitation frequencies because the corresponding man-made atoms are easier to scaled or modulated. A breakthrough based on metamaterials is for realization of optical devices in the special THz-gap region (from 0.3 THz to 10 THz) by theoretical or experimental demonstrations, which provide a kind of approaches to improve THz-based systems for several purpose-built applications. Particularly, one of the basic devices in general is a THz filter in virtue of its signal manipulation. So far there have been several researchers studying on single-band THz bandpass filters by exciting different single modes. However, fewer results focused on composite metamaterials with multi-mode excitations, i.e., two or more resonances by exciting different modes simultaneously to develop an optical device. Such composite metamaterials provide much potential for complex and powerful devices. As a result, in this letter we propose a high-profile dual-band THz bandpass filter based on three-different-mode excitation by employing a single layer of metal-dielectric-metal (MDM) composite metamaterial. To demonstrate that our designed filter can be performed under a THz radiation, we simulate the metamaterial structure in a 3-dimensional full-wave simulation based on CST Microwave StudioTM. All the simulation results successfully indicate that our designed THz filter possesses a noble capability of spectral filtering with two pronounced passbands centered at 0.97 THz and 1.37 THz, respectively. Both the passbands exhibit not only high spectral transmissions greater than 80 % but also excellent band-edge transitions in the terahertz gap. All the mechanisms for each mode are also investigated based on numerical simulation, promising a mode manipulation to exploit such electromagnetic properties. A potential device of an ultra-wide passband terahertz filter with almost 0.5-THz bandwidth after structure modulation is also demonstrated in this work.

8070-31, Session 7

Metamaterial film for solar cells

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Semiconductors are the primary materials used within solar cells. Difficulty arises in producing cost effective and efficient solar cells capable of maximizing photocurrent generation and collection. In this work, a broadband, antireflective, conductive metamaterial capable of trapping and concentrating light is proposed. This metamaterial film improves the efficiency of conventional silicon solar cells by acting as a high-performance antireflective coating and a surface-covering electrical contact. The optical properties of the metamaterial film, i.e., metal/dielectric compound aperture array, has been modeled using finite element, finite difference time domain and rigorous coupled wave algorithms. The films were subsequently fabricated and characterized. We fabricated standard control single crystalline silicon solar cells with a grid of silver wires for electrical contacts and then the solar cells with the metamaterial film serving as the antireflection coating/electrical contact/light diffuser(i.e., scatters light upon transmission into the silicon substrate). For the control and device solar cells, p-type wafers were used Wafers had average sheet resistance of 257Ω/square(representing a Boron doping density of approximately 1.0E16/cm3). Conventional POCl3 furnace processing is employed in producing the p-n junctions. A 4-point probe system confirmed the emitter layer sheet resistance to be in the range of 40-60Ω/square. Contact lithography was used to define the active regions, SiO2 film was deposited and opened using dry etch. For the control solar cells, contact pads were deposited by e-beam evaporation of aluminum and platinum. Photocurrent response measured using a current-voltage(I-V) probe station showed that when no illumination was applied, the p-n junction device was found to demonstrate classic diode behavior. When the p-n junction was forward biased (0 to -3 volts DC), the measured current grew exponentially with applied voltage. When reversed biased (0 to 3 volts DC) at the zero illumination condition, a rectifying diode behavior was observed with a dark current of roughly 0.20mA. Increasing the illumination from zero to maximum, shifts this reverse bias response. From the I-V curve, the open circuit voltage for the p-n junction occurred at 0.48V-DC, which is close to the published range(0.50-0.65V-DC) for commercial grade Si solar cells. This slightly lower value indicates our device will require annealing to improve the ohmic properties of the metal contacts. Following the fabrication and testing of the control solar cells, the solar cells with the metamaterials were fabricated and tested. First, a silicon oxy-nitride(SiOxNy) was deposited on the front surface of the wafers. A lift-off photolithography process employed, subsequently etching of SiOxNy using reactive ion etching(CHF3:O2 chemistry). Aluminum was evaporated. The wafer was left overnight in stripper to dissolve and swell the resist. SEM imaging indicated a good lift-off. Initial test show that the metamaterial film possesses superior antireflective properties to those of standard industrial single-layer silicon nitride coatings and superior electrical conductivity compared to standard solar cell Ag paste contacts. Further testing is being performed to assess the full optical and electrical performance of the film. In conclusion, our metamaterial design enables a low cost device that improves efficiency by functioning as an antireflection coating, electrically conducting light scatterer.

8070-14, Session 8

Extraordinary non-reciprocal and unidirectional effects in integrated nanophotonic magnetoplasmonic structures

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In this presentation we will give an overview of our recent work on nanophotonic magneto-optical plasmonic structures. The unique combination of nonreciprocal magneto-optical materials (dielectric or metallic) and extreme subwavelength field confinement and exaltation via surface plasmon polariton coupling on metallic interfaces or nanostructures, has led to discovery of a large variety of strongly enhanced magneto-optical phenomena or even entirely novel nonreciprocal and unidirectional effects. Our effort in this new exciting field of magnetoplasmonics combining nanophotonics with nanomagnetics includes both an investigation aimed at exploring new regimes of optics on one hand, and harnessing the unique optical properties for realization of integrated micro- and nano-optical devices,on the other hand.

In the first part of our presentation we focus on investigation of the nature of the non-reciprocal optical Bloch modes in magnetoplasmonic gratings. It will be shown that the well known enhanced Faraday and Kerr effects that appear upon extraordinary transmission through nanoperforated noble metal films on transparent MO substrates, can also be achieved by using ferromagnetic metallic gratings. Not only does this open up the possibility of easier integration on standard optical platforms such as Si and III-V semiconductors. It moreover allows the exploration of similar extra-ordinarily enhanced MO effects in integrated waveguide structures. We will show that evanescent coupling of active III-V waveguide modes to narrow subwavelength air slit in thin ferromagnetic metal films leads to surprisingly strong dispersion of the fundamental Bloch modes. It is observed that in a unique way the magneto-optical nonreciprocal dichroic loss can change sign by simply varying a geometrical parameter under fixed magnetization and wavelength. It will be shown how this strong non-reciprocal loss dispersion as a function of geometrical parameters is accompanied by an extraordinary maximization of the NR phase difference of the Bloch modes in a manner that is reminiscent of a Kramers-Kronig relationship. This opens up new possibilities for very compact integrated optical isolator circuits. Similar novel effects are expected to be found in noble metal gratings coupled to dielectric magneto-optical waveguides.

In the second part we concentrate on investigation of the unidirectional propagation as one of the most prominent effects associated with magnetoplasmonic nonreciprocity. It has already been shown that the nonreciprocal dispersion of SPP modes on gratings can be exploited to design a one-way metallic mirror for properly polarized plane waves. We demonstrate how the nonreciprocity of plasmonic modes can be taken one step further by combining a guided SPP mode on a noble metal with a magneto-optic dielectric photonic crystal. Such an integrated system can possess a one-way frequency range where only a forward propagating surface plasmon polariton (SPP) mode is allowed. In contrast to an analogous waveguide proposed by Yu[1] the non-reciprocity at the interface is introduced by the MO properties of the photonic crystal material and not by subjecting a Drude-like metal to an unrealistically high static magnetic field (~ 1T). Numerical evidence of such very compact integrated one-way magnetoplasmonic structures will be provided both by in-house developed FDTD and aperiodic RCWA tools.

8070-15, Session 8

Modified nonreciprocal waveguide formed at the interface between plasmonic metal and uniformly magnetized 2D photonic crystal fabricated from magneto-optic material

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We have demonstrated numerically that the interface of a metal and uniformly magnetized two-dimensional photonic crystal fabricated from a transparent dielectric magneto-optic (MO) material possesses a one-way frequency range where only a forward propagating surface plasmon polariton (SPP) mode is allowed to propagate. The non-reciprocity at the interface is introduced by the MO properties of the photonic crystal that is fabricated from Bismuth Iron Garnet (BIG, Bi3Fe5O12), a ferrimagnetic oxide which may be easily magnetically saturated by fields of the order of tens of mT. Therefore, this configuration allows to achieve a sizable one-way bandwidth by using significantly smaller values of the external magnetic field than an analogous waveguide proposed by Yu1 which makes such a waveguide favourable for design of diode-like elements in optical integrated circuits. By using a novel MO aperiodic Fourier Modal Method (MO a-FMM) to calculate the band structure of this magneto-plasmonic photonic crystal waveguide we have proven the existence of one-way SPP bands within the optical wavelength. To investigate transport properties of the structures within this frequency range we have implemented finite-difference time-domain (FDTD) method, that allow calculating the propagation of EM waves through media with full tensorial magneto-optic permittivity.

We examined the unidirectional transport properties of the proposed one-way waveguide and studied how the nonreciprocity depends on the intensity of the external magnetic field and when boundary conditions are modified, for instance, by placing a perfect conducting mirror at the end of one-way waveguide. By direct visualization of the time evolution of the distribution of the magnetic field and energy flow we have proved feasibility of such a waveguide configuration with non-reciprocal optical functionalities of an optical isolator and an optical circulator in optical integrated circuits.

[1] Z. Yu, G. Veronis, Z. Wang, and S. Fan:" One-way electromagnetic waveguide formed at the interface between a plasmonic metal under a static magnetic field in a photonic crystal, ", Phys. Rev. Lett. 100, 023902(2008).

8070-16, Session 8

Magnetic probe for material characterization at optical frequencies

T. J. Antosiewicz, P. Wróbel, T. Szoplik, Univ. of Warsaw (Poland)

Rapid development of novel, functional metamaterials made of purely dielectric, plasmonic, or composite structures which exhibit tunable optical frequency magnetic responses creates a need for new measurement techniques. We propose a method of measuring magnetic responses, i.e. magnetic dispersion, of such metamaterials within a wide range of optical frequencies with a single probe by exciting individual elementary cells within a larger matrix.

The probe is made of a tapered optical fiber with a radially corrugated metal coating. It concentrates azimuthally polarized light in the near-field below the apex into a subwavelength size focus of the longitudinal magnetic field component. An incident azimuthally polarized beam propagates in the core until it reaches the metal stripes of constant angular width running parallel to the axis. Light-to-plasmon coupling is assured as the lattice constant changes with the radius due to constant angular width. Bound plasmonic modes in slits between the metal stripes propagate toward the apex where circular currents in stripes and displacement currents in slits generate a strong longitudinal magnetic field. The energy density of the longitudinal magnetic component in the vicinity of the axis is much stronger than that of

all the other components combined, what allows for pure magnetic excitation of magnetic resonances rather than by the electric field. The scattered signal is then measured in the far-field and analyzed.

The probe may be used in a scanning near-field magnetic microscope for studies of magnetic responses of subwavelength elementary cells of metamaterials. Once materials with optically induced magnetism are developed the proposed magnetic field concentrator/probe may be used for magnetic write/read operations.

8070-35, Session 8

Bi-metal coated aperture SNOM probes

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Aperture probes of scanning near-field optical microscopes (SNOM) offer resolution which is limited by a sum of the aperture diameter at the tip of a tapered waveguide probe and twice the skin depth in metal used for coating. In the case of aluminum coated probes this is the norm. An increase of resolution requires a decrease of one of the above, usually the aperture diameter. However, due to low energy throughput of such probes aperture diameters are larger than 50 nm. We proposed that the the fiber core - metal coating interface be structured into parallel grooves, to convert photons into plasmons and by doing so increase the energy throughput 5-fold for Al coated probes. For metals with lower losses the enhancement is larger and in the case of Au coated probes is 30-fold. However gold coated probes have lower resolution, first due to light coupling from the core to plasmons at the outside of the metal coating, and second due to the skin depth being larger than for Al.

In this technical report we consider the impact of a metal bilayer of constant thickness for coating aperture SNOM probes. The bilayer consists of two metals of which the outer one is aluminum and the inner is a noble metal for assuring low losses, hence larger transmission. Using body-of-revolution finite-difference time-domain simulations (BOR FDTD) we analyze transmission spectra of probes without corrugations to measure the impact of using a metal bilayer. Next, we choose an optimum bi-metal configuration and investigate how this type of metalization works in the case of grooved probes.

Usage of the metal bilayer increases the energy throughput. For example, changing a 70 nm Al coating to a 70 nm Ag coating yields a 220-fold increase of transmittance. For intermediate values the transmission is between both values and increases with a larger fraction of silver. Resolution decreases slightly due to a lower skin depth of Ag, however, for certain wavelengths, for which coupling to plasmons at the outer metal interface is optimum, resolution is on the order of the diameter of the outer metal layer.

8070-36, Session 8

Effect of surface roughness on subwavelength imaging with layered metamaterial optical elements

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We characterize the influence of surface roughness on spatial resolution and transmission coefficient of layered silver-TiO2 slab-shaped or slanted-shaped superlenses. The focus is twofold. First, we investigate the effect of roughness of the external surfaces of thick slanted structures, which are capable of modifying the spatial spectrum of the optical signal and enable the interchange between propagating and evanescent parts of the spatial spectrum. Second, we study the effect of roughness of internal layer boundaries in slab-shaped superlenses consisting of only several layers. We analyze in detail single and double layer dielectric-coated superlenses. It is assumed that in the first case the structure may be treated using the effective medium theory, while in the latter we asses the importance of the surface roughness on the properties of the metamaterial, therefore making a requirement for rigorous treatment. The surface roughness is modeled using a second order Gaussian statistics based on experimental AFM measurements of e-beam evaporated layers whereas the rest of the analysis is numerical and is obtained using FDTD. Surface imperfections introduce additional scattering and thus disturb transfer of evanescent fields distorting the image. In effect, surface roughness appears to be a critical limiting factor for both superresolution and for large transmission efficiency in the layered metamaterials considered in this work. Additionally, we recall our recent results of multiscale analysis of resolution of subwavelength imaging in layerd superlenses.

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8071-01, Session 1

Nanophotonics

J. W. Haus, Univ. of Dayton (United States)

No abstract available

8071-02, Session 1

Electro-optical effects in 2D macroporous silicon structures with nanocoatings

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The near-IR light absorption oscillations in 2D macroporous silicon structures with SiO2 nanocoatings, microporous silicon layers and CdTe surface nanocrystals are investigated. The electro-optical effect was taken into account within the strong electric field approximation. Well-separated oscillations with giant amplitude were observed in the spectral ranges of surface level absorption. This process is because of resonance electron scattering on the surface impurity states with the difference between two resonance energies equal to the Wannier-Stark ladder due to big scattering lifetime as compared to the electron oscillation period in an electric field. The period of oscillations and electric field intensity in macroporous silicon structures with SiO2 nanocoatings fluctuate about constant values at low photon energy h and become quadratic in h depending on the geometrical sizes of silicon matrix and SiO2 nanocoatings. This corresponds to the electric field growth due to quasi-guided mode formation in the silicon matrix. In general, for macroporous silicon structures with nanocoatings, the near-IR light absorption is a result of electron transitions from the valence band to empty surface levels and free electron motion due to additional change of local electric field as a result of grazing light incidence and quasi-guided mode formation (for SiO2 nanocoatings only).

8071-03, Session 1

Resonance measurements techniques of optical Calcium Fluoride and fused silica whispering gallery mode mini-disk resonators for microwave photonics applications

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The aim of this work is to compare advantages and disadvantages of different techniques for coupling a mini-disk optical resonator in order to determine quality factor of its resonance. Optical fiber is coupled to a resonator consisting in a mini disk with whispering gallery modes at its circumference. We choose to work with two materials and design compact mini resonators. Fused silica is found to be suitable for this applications thanks to its hardness in the range 6-7 and the behaviour to mechanical shocks, despite the need to be careful of its sensititvity to water pollution. With its tetragonal crystal and a good behavior with risk of water pollution, Calcium fluoride is also a good candidate despite sensitivity to mechanical schoks. As a critical step, taper coupling is set with a 20 nm resolution positioning system. Microresonator was excited from a system equipped with a tunable diode laser with a tuning band from 1490 to 1640 nm and a linewidth lower than 300 kHz. Light was coupled into the microsphere either from a glass or fiber prism or with fiber taper via evanescent field. We have also possibility to use a single frequency 660 nm laser diode with linewidth lower than 100 kHz which can be tuned about 10 pm and to test if we will be able to tune it close to the single resonant peak. They were both tested with either a fiber tapered or filed fiber. Resonance was observed and quality factor of the resonators was deduced to be in the range of 10^8.

8071-04, Session 2

Intense emission of photon pairs from randomly poled nonlinear crystals

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Randomly poled nonlinear crystals are presented as efficient sources of ultra-broadband photon pairs. Photon-pair fluxes as well as spectral properties are comparable with fields coming from chirped periodically-poled crystals. The nonlinear process of spontaneous parametric down-conversion is efficient due to stochastic quasi-phase-matching that has already been widely studied in second-harmonic generation. The generated spectrally ultra-wide photon pairs have entanglement times (as measured in a Hong-Ou-Mandel interferometer) at fs time scale, which may be conveniently used in metrology. When properly phase compensated photon pairs form bi-photons which durations are comparable to that of one optical cycle. Moreover, these structures have usually smaller requirements with respect to fields' polarization properties and orientation of the nonlinear medium. Also fabrication tolerances are less strict in this case.

8071-05, Session 2

Up- and down-conversion at three-waves interaction in medium with combined nonlinear response

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We investigate an efficiency of SFG and DFG of femtosecond pulse in medium with quadratic and cubic responces of medium simultaneously. This analysis is made on the base of obtained explicit solution of set of Schrodinger equations in the frame-work of long pulse approximation both for the case of phase-matching and phase mismatching of interacting waves. Using the found explicit solution of Schrodinger equations, we make full analysis of number of solutions. We have shown the bistable regime of frequency conversion. The efficiency of SFG and DFG process strongly depends on phase mismatching, on ratio of intensities of interacting waves and on intensities of optical pulses.

Our analysis is proved by computer simulation made on the base of set of nonlinear Schrodinger equations.

It should be stressed that considered process is widely used for trebling of frequency of laser pulse. First stage is a doubling of optical frequency. Then, the second stage is a mixing of pulses with fundamental and doubling frequencies. As a consequence, a generation of laser pulse with summary frequency is obtained.

The other application of considered problem is a genration of wave with THz frequence at mixing of high intensive femtosecond pulses in medium with quadratic nonlinear response. As it is well-known for such conditions of interaction of laser pulses it is necessary to take into account the action of cubic nonlinear response also.

8071-06, Session 2

Cross phase modulation in photonic crystals

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In the last years a great progress has been made in the field of engineering optical properties of atomic media by optical means. Those investigations of fascinating both static and dynamical effects have in view far going applications in information processing, in particular constructing optical elements like quantum switches or gates.

The optical properties of a medium depend on its intrinsic level structure which can be manipulated, e.g., with the use of external electromagnetic fields. In particular, in the phenomenon of electromagnetically induced transparency (EIT) an originally strong absorption of a weak probe beam in the -configuration medium is suppressed by switching an additional strong control field. This allows, e.g., for pulse slowdown, storage and retrieval.

A number of new interesting possibilities of controlling the pulse propagation are present in the four-level tripod system which provides additional degrees of freedom. In particular, a simultaneous propagation of two pulses (called probe and trigger) in such a medium can be considered. In EIT-like conditions a usually weak interaction between two photons (or weak classical pulses) may become enhanced by many orders of magnitude. This gives rise to nonlinear effects, i.e. large cross phase modulation which allows for constructing a polarization phase gate (see [1]).

A wide area of investigations opens when the control field is taken in the standing wave form, leading to periodic modulation of the refractive index of the medium in the length scale comparable to optical wavelength. Such a material is called a photonic crystal.

In the case of the tripod medium the periodic structure leads to Bragg scattering of each of the incident beams. Thus, both probe and trigger are split into two (transmitted and reflected) components the phase shifts of which are of particular interest.

In our work (see [2]) we find the nonlinear electric susceptibility of the periodic tripod medium for both probe and trigger. We describe the pulses' propagation in terms of Maxwell-Bloch equations, find their approximate solutions and make a number of numerical simulations in such a system for different values of parameters characterizing the system, i.e. the probe and control fields' intensities and detunings, the relaxation rates, the length of the sample, etc. This way the phase shifts of each of the beams are obtained. The optimal conditions are sought in which the probe nonlinear phase shift induced by an interaction with the trigger is large for both transmitted and reflected beams. We show that the relative phase shift of the two beams can be manipulated in a convenient way by changing the frequency of the incoming probe. The transmission and reflection spectra are obtained for different values of parameters characterizing the system.

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8071-07, Session 2

Two telescopes ABCD electro-optic beam combiner based on Lithium Niobate for near infrared stellar interferometry

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Lithium Niobate (LN) based electro-optic modulators are well known in the field of optical communications, due to their high bandwidth and deep rejection ratio [Porte07]. These performances could be used in the field of astronomy for nulling interferometry in the mid-infrared domain [Monnier09]. With our partners from Photline Technologies, we have conceived, developed and characterized a 2T ABCD [Shao88] beam combiner in the near-infrared (1.5um, the H-band in astrophysics). The modulation scheme allows to determine the fringe characteristics in a single shot measurement, without the need to externally scan the optical phase delay. The imperfections of the fabrication procedure can be finely tuned using the electro-optic properties of the lithium niobate, in particular, the phase on each output can be electrically controlled and locked by using appropriate electrodes.

These devices have to ensure modal filtering to reject optical aberrations of the wavefront and thus optimize the fringes contrast, which means that they have to be single mode through all the spectral range of interest. This also means that the couplers should be achromatic. We will present results on global transmission, performance of the couplers and electro-optic behavior of the device using monochromatic as well as wide spectral sources in the H-band.

Preliminary results on the output state as a function of the applied voltage are shown in the figure below.

This voltage is applied between the two inputs, in order to shift simultaneously the ABCD outputs through the fringes and locate the nominal point, where A is at maximum, C is at minimum, and D and B are in a similar intensity state. As seen in the figure, the AC optimum is obtained at V=0.77V, whereas the BD optimum is obtained at V=0.96V. Thus, the coupler is slightly asymmetric, and this effect can be compensated using a differential voltage on the upper arms of the device (concerning only outputs B and D). We can also observe that although the device is symmetric in the A-C and B-D functions, different outputs are not equally compensated: minimum flux for C is 10% whereas for A it never goes below 17%.

These preliminary results are encouraging for applications in astronomical instruments, as recently achieved with passive Silica/Silicon beam couplers [ESO2010]. Discussion on how to improve these couplers in terms of achromaticity, in particular using photonic crystals, and their potential on higher wavelengths (mid-IR) will also be presented.

8071-08, Session 2

Strong modification of density of optical states in biotemplated photonic crystals

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The photonic density of states (DOS) is directly proportional to radiative transition dynamics, according to Fermi's Golden Rule. Next generation applications in solar energy conversion, solid-state lighting and lasing, along with quantum information processing, rely on radiative process control and therefore strategies to manipulate the radiative DOS over broad frequency ranges are of paramount technological importance. Many of these applications require a three dimensional lattice of dielectric material with feature sizes on the order of hundreds of nanometers, called photonic crystals. We have used photonic crystal to experimentally probe the relationship between structure, DOS, and radiative dynamics. While photonic crystals, have been thoroughly investigated computationally, experimental examples have generally been limited to those created through colloidal self-assembly methods. Unfortunately these structures offer only a modest impact on the rate of spontaneous emission, reflecting a minor modification of DOS.

Recently, however, we developed a bio-inspired approach that takes advantage of the wide variety of photonic structures in nature not currently available through synthetic methods including diamond-based lattices reflective in the visible.1 Silica and titania photonic crystal structures have been patterned from the cuticular scales of a variety of weevils containing a diamond-based lattice using sol-gel chemistry.2 By slightly altering the methods used solid inverse, hollow inverse, and replica structures were made out of titania and silica, highlighting the utility and versatility of sol-gel techniques to make biotemplated photonic crystals. These structures were characterized using SEM, and optical microscopy. Photonic band structure and DOS calculations show that these photonic crystals significantly alter the DOS, showing that photonic crystals need not possess a full photonic band gap in order to significantly alter the excited state dynamics of emitters embedded within them. Time correlated single photon counting (TCSPC) on the emission from quantum dots embedded in a high dielectric biotemplated sample confirm these calculations. The radiative lifetime of quantum dots measured in the photonic band gap of our material show an unprecedented inhibition of a factor of

10 compared to the same quantum dots measured outside of the photonic band gap. New insights into photonic structure design, highlighting the relationship between DOS and various structural parameters will also be discussed.

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8071-09, Session 3

Nonlinear plasmonics

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No abstract available

8071-10, Session 3

Enhancement of second harmonic generation in coupled chains of Ag rods

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We report numerical results showing that second harmonic generation can be enhanced and tailored by resonant excitation of coupled localized plasmon polariton modes in chains made of multiple Ag blocks. Our calculations show that strong field localizations are obtained in the region between the rods resulting from interference of localized surface plasmons when the fundamental field is tuned on a coupled resonance. Further investigation of the near field and far field properties of the generated field reveals that the second harmonic signal is extremely sensitive to the features of the gap region. Also, the far field emission pattern depends on the position of the hot spots and can be controlled by proper tuning of the frequency of the pump beam. This feature could allow for example, to detect the position of a molecule filling one gap or to realize an array of nanosources for single molecule fluorescence experiments.

8071-11, Session 3

Nonlinear circular dichroism from self-organized metal nanowires arrays

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Metal nanostructures supported on dielectric substrates have attracted great interest as building blocks of nanoscale optical devices such nano-plasmonic devices or planar metamaterials. In this framework artificial circular dichroism is investigated for developing novel devices for active polarization controllers, like rotators and modulators and high efficient molecular sensors. Here we report the experimental observation of nonlinear extrinsic chirality (circular dichroism) of the second harmonic (SH) field generated by self-organized gold nanowire arrays with sub-wavelength periodicity. In this material the chirality arises from the curvature of the self-assembled wires, producing a lack of symmetry at oblique incidence. Such circular dichroism in the SH field is the evident signature of the sample morphology and can be used in order to develop more efficient molecular sensors, based on metal enhanced fluorescence or surface enhanced Raman scattering.

8071-12, Session 4

Nonlinear and active plasmonics

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Recent advances in nanofabrication and nanoscale optical characterisation have led to the development of novel plasmonic metamaterials with numerous applications in photonics and optoelectronics. Metamaterials based on metallic nanostrucrures are considered as the basis for implementation of nanoscale waveguides, integratable wavelength selective devices, negative refraction, superlenses, electromagnetic shielding as well as optical materials with the enhanced effective nonlinearity. Implementation of active nanophotonic devices additionally requires an opportunity to control optical response of metamaterials with external signals. The hybrid plasmonic metamaterials consisting of nanostructured metals combined with functional dielectrics can be controlled with external static electric and magnetic fields as well as all-optically.

In this talk we will discuss various realizations of optically tuneable plasmonic metamaterials. Our approach takes advantage of a very high sensitivity of surface plasmon mode dispersion to the refractive index of the adjacent dielectric. Hybridization of plasmonic nanostructures with molecular species exhibiting nonlinear optical response allows the development of metamaterials with high effective nonlinear susceptibility due to the electromagnetic field enhancement related to plasmonic excitations and with plasmonic modes that are highly sensitive to the refractive index changes. In such systems, signal and control light can be coupled to plasmonic modes that strongly interact via nonlinearity introduced by the hybridization.

Plasmonic metamaterials with tuneable optical properties can be used to control negative refraction and electromagnetic field propagation in various applications in nanophotonics, optoelectronics and optical communications. Optical metamaterials with the enhanced nonlinear response at very low control light intensities are also needed in nanophotonic elements capable of performing, all-optically, logic operations analogous to their electronic counterparts without optical-to-electronic and electronic-to-optical signal conversion and imperative for implementation of nanophotonic integrated circuits.

8071-13, Session 4

Nonlinear optical properties of silver nanoparticles synthesized in ORMOCER by ion implantation

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First experimental results on a synthesis of metal nanoparticles in ORMOCER by ion implantation and nonlinear optical properties of such composite are presented. Silver ions were implanted into organic/inorganic matrix at an accelerating energy of 30 keV and doses in the range from 0.25·1017 to 0.75·1017 ion/cm2. The silver ions form metal nanoparticles, which demonstrated surface plasmon absorption at the wavelength of 425-580 nm. The nonlinear absorption of composites was measured by z-scan technique using 150 fs laser pulses at 780 nm. ORMOCER with silver nanoparticles shows nonlinear saturation absorption, than matrix itself demonstrates two-photon absorption. Superposition on two nonlinear absorptions in same composite material is discussed.

8071-14, Session 4

Light up-conversion and single photon directional emission beaming from quantum dots embedded in subwavelength metallic nano-slit arrays

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We show a large, 20-fold enhancement of two-photon absorption processes in nanocrystal quantum dots and of light upconversion using a hybrid optical device in which near-IR emitting InAs nanocrystal quantum dots were embedded in a metallic nanoslit array. We also demonstrate a directional beaming of the photons that are emitted

from these quantum dots with a divergence angle of less than 4 degrees. The resonant enhancement of the nonlinear optical processes is due to the strong local electromagnetic field enhancements inside the nanoslit array structure at the extraordinary transmission (EOT) resonances. The photon beaming is achieved using the resonant coupling of the quantum dots excitonic optical transitions to the Bragg standing EOT modes, where exciton-plasmon polariton coupling dominates the emission properties of the quantum dots. We show this beaming effect down to the single quantum dot - single photon level. Our experimental results are compared to theoretical calculations of the electromagnetic field intensities of the structures' resonant plasmon modes, and of the optical coupling of single quantum dots to such resonant plasmon modes, and show a very good agreement to both the upconversion and the photon beaming processes. This agreement confirms the suggested picture for the underlying physical mechanism behind the observed effects.

Therefore we conclude that engineering structures that selectively incorporate nanocrystal quantum dots with subwavelength metallic nanostructures is a promising way for a range of new types of active optical devices, allowing new ways to manipulate and control the optical properties of these nano-emitters.

8071-15, Session 5

Attosecond production

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No abstract available

8071-16, Session 5

Isolated attosecond pulses: generation and application to molecular science

M. Nisoli, Politecnico di Milano (Italy)

No abstract available

8071-17, Session 5

Optimization and characterization of a femtosecond tunable light source based on the soliton self-frequency shift in photonic crystal fiber

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We report here an extensive experimental study dealing with the optimization and the full characterization of a photonic crystal fiber (PCF)-based light source for generating femtosecond tunable pulses that are suitable for coherent anti-Stokes Raman scattering (CARS) microscopy. Starting from a commercial femtosecond oscillator operating at 1033 nm and which delivers 20 nJ/ 190 fs Gaussian transformed-limited pulses (Amplitude tPulse device), we have taken advantage of the soliton-self frequency shift (SSFS) that induces through Raman scattering a continuous shift of the central wavelength of any ultrashort pulse propagating in a silica fiber.

As a first optimization step, we have experimentally tested the performance of three commercially available PCFs exhibiting distinct group velocity dispersion (GVD) characteristics. The spectral profile of GVD has been found to highly impact the range of tunability of the SSFS process, the presence of a second zero dispersion wavelength being a physical limit. Consequently, a single zero dispersion wavelength has been favored in our set-up. Value of the anomalous dispersion also affects the Power Spectral Density (PSD) : as frequency shifted pulses are fundamental solitons, the PSD is directly proportional to the ratio of the GVD over the nonlinearity. Using high dispersion value at the pump wavelength, we have achieved a 300 µW/nm PSD, which is well above the requirement for CARS microscopy (around 50 µW/nm). Note that a high dispersion fiber also limits the generation of additional solitonic structures as well as the energy transferred in blue shifted dispersive waves so that a good conversion efficiency from the pump to the frequency shifted signal can be obtained (around 30% in our case).

Regarding the spectral shift that we have achieved, a maximum frequency shift of 340 nm has been obtained which enables to probe up to 2400 cm−1. The tunability is achieved by simply adjusting the power launched in the PCF and a close to linear dependence of the frequency shift versus the initial power has been recorded. The tunability range has experimentally been limited by the OH absorption of the fiber, constraint that should be easily removed with newly designed low-OH PCFs. Autocorrelation measurements have confirmed that the frequency shifted pulses are nearly transform limited with an output pulse duration of 100 fs.

Additional measurements based on radio-frequency (RF) spectrum analysis were finally carryed out in order to estimate the level of amplitude and timing jitters of the output pulses. 0.15% intensity noise and 300-fs timing jitter for any wavelength shifts of the femtosecond soliton pulse have been demonstrated, those values being quite similar to the jitters of the initial oscillator. All the various measurements done have been found to be highly reproducible, which confirms that this wavelength tunable soliton source is stable and should be fully suitable for future applications in the context of CARS microscopy.

8071-18, Session 6

Ultrafast quantum and nonlinear optics with optical antennas

X. Chen, A. Baradaran Ghasemi, V. Sandoghdar, M. Agio, ETH Zurich (Switzerland)

The enhancement of light emission with metal nanostructures has gained considerable attention in the recent years across a broad range of areas from biophotonics to quantum optics. Under continuous weak excitation, it is well established that the fluorescence signal is proportional to the field intensity and to the apparent quantum yield. The latter accounts for the competition between the radiative and non-radiative decay rates, which are strongly modified by the presence of an optical antenna. Extensive investigations have shown that huge field enhancements can coexist with large quantum efficiencies, making these systems appealing for quantum and nonlinear optical applications down to the single-molecule level [1]. On the other hand, time-resolved techniques, such as pump-probe spectroscopy, coherent control, all-optical switching and triggering single-photon sources, to mention a few, rely on (ultrafast) pulsed excitation. The immediate question that arises is thus how an optical antenna affects the response of a (few) molecule(s) under laser pulses of various widths and intensities, at room and cryogenic temperatures. Here the important points of concern are the competition between decay times, dephasing and pulse width, the increased interaction strength and saturation due to field enhancements, and the dispersion occurring when the pulse duration becomes comparable with the lifetime of the antenna resonance. We have developed a formalism that allows us to perform a detailed analysis of these phenomena and found that pulsed excitation discloses new challenges and opportunities for optical antennas [2]. We present our findings in a context that ties ultrafast nano-optics with quantum and nonlinear optics. Exploring ultrafast nonlinearities at the few-photon level and at the nanoscale could lead to fundamental contributions on the way to new nano-devices for optical communication and computation [3].

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8071-19, Session 6

Deep UV generation and fs pulses characterization using strontium tetraborate

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Strontium tetraborate (SBO) is attractive for nonlinear optics due to its transparency window that allows nonlinear optical conversion to the wavelengths down to 125 nm. It possesses largest nonlinearity among crystals transparent below 270 nm. Angular phase matching and standard QPM in SBO are absent. Phase matching is, however, possible due to random QPM using one-dimensional nonlinear photonic crystal (NPC) structures. These NPC are of growth origin and cannot be formed in desired geometry, but their properties depend on the growth process. Different types of NPC possess different nonlinear properties and must exhibit different spectral dependence of frequency conversion efficiency. Due to high randomness of NPC obtainable using existing technology, these spectral dependences for NPC SBO typically protrude from near IR to near UV in the fundamental wave scale. Real NPC structures in SBO can be roughly classified into three groups with different domain distribution and different ratio of aggregate thickness of domains with two opposite static polarisation directions. Their calculated spectral dependences are commonly similar but differ in important details. Particularly, the width of individual peaks can become smaller than bandwidth of fs lasers whether in IR or in the visible. The drop of spectral dependence in the short wavelength region ensues whether in IR or in UV in different NPC structures. Experimental study of these structures is reported for the process of doubling of the second harmonic of fs Ti:S oscillator. The second harmonic average power used for testing was in the range of 60 - 135 mW. Tuning of generated radiation is obtained in the range 187.5 - 232.5 nm, with extreme insensitivity to the angular orientation of NPC. However, the spectrum of generated DUV radiation is distorted into peaky structure, as can be expected from calculations. Behaviour of tuning curve along investigated fundamental wave range is similar in all studied samples. Spectral quality of generated radiation is experimentally shown to grow better when using NPC with improved structure. Conversion efficiency in the NPC with improved structure is 2-3 times higher in the DUV region, too. Output average DUV power was of order of several hundred nanowatts to several microwatts. Prospects of broadband angle-insensitive VUV converter on a single NPC are discussed, and requirements to the desired NPC structure are formulated. The concept of NPC band structure is discussed, and experimental proof for the red rotational shift of NPC band structure is presented, in contrast to blue rotational shift of the linear PC band structure.

8071-20, Session 6

Control of group velocity of a light pulses propagating through four-level atomic system

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We analyze the group velocity of a laser pulse in an optically dressed atomic system. A system with two closely spaced upper levels is specially investigated. The group velocity of a pulse is strongly depended on the optical properties of the system which can be modified by changing the amplitude or detuning of strong coupling field or incoherent pump between the two lover levels of the system. Depending on the parameters the medium may have alternatively absorptive or gain properties and the dispersion can be changed from abnormal into a normal one. The ranges of parameters are especially investigated in which absorption (gain) is not too strong, with dispersion being not too steep. The group velocity of a pulse propagating through a sample with such optical properties can be switched from sub- into the superluminal regime.

The dynamics of propagation in the case of negative group velocities of a small absolute value is especially interesting. In such a regime the peak of the transmitted pulse exits the sample before the peak of the incoming pulse reaches the medium. The transmitted pulse splits into two pulses - one of them propagates forward behind the medium and the other propagates backward and is cancelled at the entrance of the sample by the incoming pulse.

The propagation of a pulse is also studied in terms of presence of a Brillouin precursor which has been observed under some conditions.

Our main results based on numerical calculations will be shown as a comparison of a two methods of approximation of the electric susceptibility of the medium.

8071-21, Session 6

Permanent wavegides in glassy As4Ge30S66 induced by femtosecond filaments

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Chalcogenide Glasses (ChGs) are important photonic materiasl due to their wide IR-transparency and high nonlinear refractive index. On the other hand, femtosecond laser beam is a new effective tool for fabrication of photonic devices in photosensitive transparent materials, particularly ChGs. Here we report the first observation of the femtosecond filaments and filament-induced permanent waveguides in bulky ChGs exemplified by a glassy As4Ge30S66. This wide-energy-gap (3.0 eV) ChG belonging to Ge-enriched composition within quasi-binary GeS2-As2S3 cut-section has been specially synthesizes to reduce the two-photon absorption (2PA), which normally prevents the filament formation in more narrow-gap ChGs. In the experiment we focus the femtosecond laser beam (110 nJ, 150 fs, 800 nm, 1 kHz) into a plane-parallel 3 mm thick optically finished sample at different pulse energies, exposures T, and positions of the beam waist inside the sample. Time-integrated near-field profiles of the beam are measured at the exiting face of the sample. The reversible Kerr filament featuring 4.8 µm core diameter and up to 1.8 mm length is recorded in the material at $T \leq 10$ s. At longer exposures $T \geq 25$ s, the refractive index change appears in the material on the filament axis forming a permanent waveguide, capable of guiding a low-intensity (1.4 nJ) laser pulse. We conclude that two principal mechanisms are involved in the waveguide formation. First the Kerr filament forms, while the formation of the permanent waveguide occurs later due to the gradual positive Δn build-up on the filament axis. The latter process gives rise to the further beam narrowing (down to 2.8 µm) as a result of its self-trapping in the induced waveguide. A physical reason for the permanent index change is the generation of free carriers by 2PA in the filament core. After the trapping, these carriers trigger structural transformation in the material, which results in the permanent refractive index change. The refractive index profile of the waveguide is numerically recovered from its defocused microscopic transmission images, applying 1D transport-of-intensity equation and inversed Abel transform. It has been assumed that the waveguide is a purely phase object. The index profile features the positive index change up to 0.5 10-3 in the zone of ~3 µm diameter along the axis, enveloped by a zone of negative change of ~7 µm diameter. Such a shape of the profile suggests that densification of the material is responsible for the axial increase of the index, while the tensile stress generates the area of decreased index around the axis.

8071-22, Session 6

Frequency doubling of picosecond pulses generated by a monolithic DFB tapered MOPA in a ppMgO:LN channel waveguide

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Laser light sources emitting picosecond pulses (tau_FWHM < 200 ps) at 532 nm with a good beam quality (M^2 ≈ 1) and a moderate pulse energy (E > 50 pJ) at variable repetition rates in the MHz range are desired for applications such as time resolved fluorescence spectroscopy. Frequency doubling of near-infrared (NIR) diode laser radiation in a channel waveguide allows to realize such devices in a compact manner.

In this work, we investigated experimentally second-harmonic generation (SHG) of picosecond pulses in a channel waveguide. A dependence of the second-harmonic (SH) pulse duration on the NIR pulse energy as well as a distinctive influence of the waveguide structure on the beam quality was observed. A maximal SH peak power of 0.75 W was achieved. The corresponding opto-optical conversion efficiency was 24 %.

As a pump source, a 4 mm long monolithic distributed feedback (DFB) master-oscillator tapered power-amplifier (MOPA) [1] was used. The DFB tapered MOPA consists of three individually contacted sections: a 1 mm long DFB section, a 1 mm long index-guided pre-amplifier section and a 2 mm long tapered amplifier. The taper full angle is 6°. The SHG was performed in a 11.5 mm long periodically poled 5 %mol MgO doped LiNbO_3 (ppMgO:LN) crystal with a ridge waveguide.

During the experiment, the DFB section was electrically pulsed, while the amplifier sections were biased using direct current. The laser emitted picosecond pulses at a repetition rate of 10 MHz. The central wavelength of 1063.4 nm with a corresponding spectral width of 130 pm (FWHM) was determined with an OSA. The beam quality parameter M^2 was estimated to 1.8 vertically and 2.5 laterally through a caustic measurement using the second order moments method. A maximum NIR pulse energy and peak power of 560 pJ and 3.2 W was generated, respectively. The pulse form was measured with a 20 GHz photodiode and a 25 GHz oscilloscope input. The NIR pulse duration (FWHM) was determined to 136 ps. A distinctive improvement of the SH beam quality compared to NIR beam quality was observed due to the influence of the channel waveguide. A SH pulse energy and pulse duration of 136 pJ and 134 ps was reached, respectively. The generated radiation is perfectly suited for time resolved fluorescence spectroscopy.

At the conference, we will present the SH energy dependence on the increasing NIR energy and on the crystal temperature. We will show how the SH beam quality is improved by the channel waveguide compared to the NIR beam quality and how the SH pulse duration depends on the NIR pulse energy. Furthermore, the time and the spectral characteristics of the NIR and SH radiation will be shown.

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8071-36, Poster Session

Experimental study of second harmonic generation in PPKTP crystals using high-power ytterbium fiber laser

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Second harmonic generation (SHG) is widely used technique for frequency doubling of a coherent light used mainly in the cases when direct quantum transitions are not available. SHG by means of nonlinear birefringent crystals suffers from relatively short interaction length due to spatial walk-off of the pump and signal beam. Longer interaction length can be obtained in quasi-phase matched materials, e. g., in periodically poled crystals, as for instance lithium niobate (LiNbO3), and potassium titanyl phosphate (KTiOPO4, KTP) [1, 2]. Such crystals are advantageous also for other applications like fast pulse shaping and optical parametric amplification or oscillation. Periodically poled crystals pumped by fiber laser can be utilized in compact, high-power and efficient sources at various wavelengths [3]. Reasonably efficient SHG can be achieved even in continuous-wave regime that is required for several applications [4, 5].

In this paper we investigate experimentally the efficiency of SHG in periodically poled KTP (PPKTP) crystals using ytterbium-doped fiber lasers. The PPKTP crystals are poled with proprietary technology, which allows control over the progress of the poling process in the whole volume of the poled crystal. Typical crystal dimensions used in the poling process are 12x11x1mm3. After the poling they are cutted into smaller crystals of 2.5mm width and 11mm propagation length. We have built ytterbium-doped fiber laser with aim to check the spatial homogeneity of SHG conversion efficiency of fabricated PPKTP crystals and to determine their quality by comparing their SHG efficiency at certain conditions.

Special attention is devoted to maintain stable continuous-wave and linearly-polarized operation of the fiber laser. The laser is in ring configuration. Multimode laser diodes at 980nm are coupled with ring laser cavity to pump ytterbium-doped double-clad fiber. The fiber-Bragg-grating (FBG) defines the output wavelength of the laser to 1064nm. Since the FBG works in reflection, it is included into the ring cavity via polarization-maintaining optical fiber circulator. Output wavelength of the fiber ring laser is tunable by stretching the FBG and output power is up to 5W.

The fiber laser characteristics including tunability were measured. Three PPKTP samples with grating period of 9.02um suitable for 1064nm conversion and having length 11mm were characterized. Their conversion efficiencies, temperature, wavelength and angle acceptances are presented.

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8071-37, Poster Session

Optoelectronic phase noise system designed for microwaves photonics sources measurements in metrology application

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The performance advances in communication systems as well as Radar system, precision navigation, space application and time and frequency metrology require more stable frequency and low phase noise system. In this paper we present a configuration of phase noise measurement system operating in X- band using a photonic delay line as a frequency discriminator. The main advantage of this system is that it does not require an excellent frequency reference and works in any range of microwave frequencies between 8.2 and 12.4 GHz. At 10 GHz, the noise floor for a 2 km delay line is respectively -145 and -163 dB rad²/Hz at 100 Hz and 100 kHz with 200 averages using cross correlation method. The sensitivity of our system allows characterizing sources on a larger Fourier frequency interval around the carrier by commuting two lines with different length. This system is designed for microwaves photonics sources and it is a way of characterizing non linearities appearing when optical power begins to be to high inside chrystal. Developed in the context of association with the national french metrology institute (laboratoire national de métrologie et d'essais, LNE), this calibration system is to be integrated in measurements means of the accredited laboratory to improove the Calibration Metrology Capabilities (CMC) of the LNE.

8071-38, Poster Session

Numeric investigations in attophysics: the stabilization phenomenon

J. Matulewski, T. Dziubak, Nicolaus Copernicus Univ. (Poland)

The dynamics of ionization and recombination in an ultrastrong laser field is studied by ab initio numerical simulations performed for 3D realistic atomic system in the regime of an attosecond laser pulse duration. In particular the stabilization phenomenon is studied, which presence is confirmed in 3D. The applicability of 1D model are also studied.

8071-39, Poster Session

Ultrafast photonic switching based on the protein bacteriorhodopsin

L. Fábián, Z. Heiner, Biological Research Ctr. (Hungary); M. Mero, M. Kiss, Univ. of Szeged (Hungary); E. K. Wolff, Univ. Witten/Herdecke GmbH (Germany); P. Ormos, Biological Research Ctr. (Hungary); K. Osvay, Univ. of Szeged (Hungary); A. Der, Biological Research Ctr. (Hungary)

The continuous growth of internet traffic is expected to last for the foreseeable future. The concept of 1 Tbit/s Ethernet represents the expectations of a serious improvement both in capacity and speed of data trafficking. It is generally believed that all-optical data processing is the most promising direction to achieve these goals. The state-of-the-art photonic integration technology is ready to provide the passive elements of the optical integrated circuits, based either on silicon, glass or plastic materials. The bottle-neck is to find a proper nonlinear optical (NLO) material that is supposed to be a cladding medium ("adlayer") in waveguide-based integrated optical circuits performing light-controlled active functions.

Two recent papers in Science suggest that the currently used inorganic semiconductor NLO materials are expected to give place to more versatile and cost-effective organic materials [Haque and Nelson, Toward organic all-optical switching. Science, 327, 1466-1467 (2010), and Hales et al., Design of polymethine dyes with large third-order optical nonlinearities and loss figures of merit. Science 327, 1485-1487 (2010)]. Specifically designed Pi-conjugated molecular materials have attracted so far the highest attention. These developments inspired us to present our latest results achieved by an alternative approach: We succeded in demonstrating ultrafast photonic switching by a biomaterial, the chromoprotein bacteriorhodopsin (bR).

Nature readily provides us with pi-conjugated materials optimized for sensing light during myriads of years of evolution. Although biological materials in general are disregarded in technical applications because of their fragile nature, there are some proteins, like bR, that are extraordinarily robust, so their biological origin does not represent a practical disadvantage in any respect, while, on the contrary, they offer special advantages which can be exploited in bioelectronic applications. (E.g. the use of genetic engineering techniques to taylor spectral properties of the biomaterial.)

In 2002, we demonstrated the first integrated optical switching by bR, with a switching speed of ca. 1 μs [Ormos et al., Protein-based integrated optical switching and modulation. Appl.Phys.Lett. 80, 4060-4062 (2002)]. Later on, we improved the switching time to ca. 10 ns [Fábián et al., Fast integrated optical switching by the protein bacteriorhodopsin. Appl. Phys. Lett. 97, 023305 (2010)], still behind the state of the art (some 100ps). The present results, however, represent a breakthrough: we demonstrate switching speeds increased by four orders of magnitude, to subpicosecond switching times, well beyond the present state of the art. This superior performance brings biomaterials to the frontline of modern photonic technology.

8071-40, Poster Session

Obtaining $ZnO/CuInSe_2$ heterostructures

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We obtained ZnO/CuInSe2 heterostructures by sequential elemental evaporation. Such structures can be applied in nonlinear optics, photovoltaic and so on.

Firstly, layer of Zn was evaporated on unheated glass substrate by ion sputtering method in vacuum. Needle-shaped nanostructures of ZnO have been grown by thermal annealing in air of prepared Zn films with different thickness. Secondly, onto these structures In and Se layers were sequential deposited by thermal evaporation method and Cu layer - by ion sputtering method in vacuum. Obtained samples were annealed at 4000C to form CuInSe2 (CIS). Morphological, structural and compositional characterizations of these films were carried out by scanning electron microscopy, energy-dispersive X-ray spectroscopy and X-ray diffraction analysis methods. Optical and electrical properties of these structures were also investigated.

8071-41, Poster Session

Multi-threaded parallel simulation of non-local non-linear problems in ultrashort laser pulse propagation in the presence of plasma

M. Baregheh, Aston Univ. (United Kingdom); H. Schmitz, Imperial College London (United Kingdom); V. K. Mezentsev, Aston Univ. (United Kingdom)

We describe a parallel multi-threaded approach for high performance modelling of wide class of phenomena in ultrafast nonlinear optics. Non-linear wave equation in the form of the Generalised Non-Linear Schroedinger Equation (GNLSE) is a generic mathematical model describing narrow bandwidth wave propagation in envelope approximation. In this paper we consider a parallel numerical solution for a specific model which describes femtosecond laser pulse propagation in transparent media. In this case GNLSE is coupled to Drude model of plasma resulting from multi-photon and avalanche ionisation processes. However our approach can be extended to similar models. We compare performance of the multithreaded parallel code implemented for Nvidia Graphics Processing Units (GPU) using CUDA programming interface with a serial CPU version. Efficient use of GPU's parallel resources requires radical revision of the current pipelined method. Coupling between the equations makes GNLSE non-local which results in impossible straightforward parallel implementation.

To simplify the problem, the splitting operator method is used to reduce GNLSE it into a succession of linear and non-linear steps. The linear term is solved in frequency domain using CUDA's multi-threaded version of the Fast Fourier Transform. The parallel simulation of the non-linear term is not straightforward due to non-locality induced by coupling between plasma and electromagnetic wave. We develop the parallel numerical solution of non-linear step by expressing the non-linear problem as an integral equation in time domain. Partial integrals are then delegated for simultaneous calculation performed by concurrent threads.

We have managed to successfully parallelise solution of GNLSE non-locally coupled with plasma using multi-threaded GPU architecture. We have tested the accuracy of the results and found satisfactory linear scaling up with 10x to 30x factor of speedup on Nvidia Tesla C1060 compared to CPU implementation.

8071-42, Poster Session

Stability analysis of second order pulsed Raman laser in dispersion managed systems

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Wavelength tunable synchronous pulse sources are highly desirable for spectroscopy and optical diagnostics. The common method to generate short pulses in the fiber is the use of nonlinear induced spectral broadening which result in soliton shaping in anomalous dispersion regime. However, to generate ultra-short pulses, broadband gain mechanism is also required. In recent years, Raman fiber lasers have retrieved strong interest due to their capability of serving as pump sources in gain-flattened amplifiers for optical communication systems and as widely tunable sources to characterize the optical devices at longer wavelengths. The fixed-wavelength Raman lasers have been widely studied in the last years, but recently, much focus has been on the multi wavelength tunable Raman fiber lasers which generate output Stokes pulses in a broad wavelength range by so called cascaded stimulated Raman scattering. In this paper we investigate synchronous 1st and 2nd order pulsed Raman lasers that can achieve frequency spacing of up to 1000cm-1 that is highly desired for CARS microscopy. In particular, analytical and numerical analysis of pulsed stability derived for Raman lasers by using dispersion managed telecom fibers and pumped by 1530nm fiber lasers.

To generate stable pulsed lasers by Raman process, dispersion management of pump, first order and second order pulses is the utmost important parameter. Most of the commercial DSFs and SMFs have high dispersion values and slopes, and hence it is not possible to maintain a reasonable walk-off (overlapping of pulses) through the propagation. To eliminate walk off and perform stability analysis dispersion managed system is proposed. The main objective of the analysis is to determine if the output Stokes pulses converge to dispersion managed solitons at steady state. Split Step Fourier Method (SSFM) is being used to solve the coupled NLS equations numerically. Additionally, the propagation of Stokes pulses at steady state are modeled by using variational analysis method which assumes the signal maintains its shape even though its power, pulse width and chirp changes in a continuous manner and remains same periodically after each round trip by taking signal to signal interactions into consideration such as XPM, Raman amplification and walk off to analyze the pulse dynamics.

We show the evolution of the 1st and 2nd order Stokes signals at the output for different pump power and SMF length (determines the net anomalous dispersion) combinations. We investigated the stability of dispersion managed synchronous Raman laser up to second order both analytically and numerically. The results show that the stable 2nd order Raman Stokes pulses with 0.04W to 0.1W peak power and 2ps to 3.5ps pulse width can be achieved in DM system. Results can be further improved by optimizing the parameters of the dispersion management.

8071-43, Poster Session

Effects of nonlinear gain and thermal carrier escape on dynamic characterizations of GaAs/InGaAs self-assembled quantum dot lasers

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In this paper we have studied the effects of nonlinear gain and thermal carrier escape on dynamic characteristics of GaAs/InGaAs self-assembled quantum dot laser with considering the homogeneous and inhomogeneous broadening of the optical gain using fourth order Runge-Kutta method. Our calculations show that the thermal carrier escape leads to shift the dominant lasing mode at the low injection currents. The number of lasing modes increases for the larger injection currents. With exceeding the FWHM of homogeneous broadening from the full width at half maximum FWHM of inhomogeneous broadening the dynamic and static-characteristics degrade and SAQD-LD reaches the steady-state slower. The threshold current, the steady-state photons and the dynamic-characteristics degrade and SAQD-LD reaches the steady-state slower as the FWHM of inhomogeneous broadening and carrier relaxation life time increase.

8071-44, Poster Session

Large picosecond nonlinearity in gold nanoparticles synthesized using Coriandrum sativum extract

S. Venugopal Rao, Univ. of Hyderabad (India)

The optical nonlinearity of nanomaterials varies with size, shape, distribution, host environment, etc. and rapid synthesis routes provide an excellent opportunity to understand and thereby control their physical, optical, and NLO properties. Synthetic methods based on naturally occurring biomaterials provide an attractive alternative and environmental-friendly means. Recently, several groups have successfully achieved the synthesis of Ag, Au, Pd nanoparticles using extracts obtained from unicellular organisms such as bacteria, fungi, plant extracts etc. We have been successful, through our recent efforts, in synthesizing silver nanoparticles using simple and bio-inspired method using the leaf broth of coriandrum sativum and Moringa oleifera, for the first time, as both the reducing and stabilizing agent We present our results on the nonlinear optical (NLO) studies of gold nanoparticles synthesized using coriander leaves (Coriandrum sativum) extract. Nanoparticles with an average size of ~30 nm (distribution of 5-70 nm) were synthesized according to the procedure reported by Narayanan et al. [Mat. Lett. 2008; 62: 4588-91]. Picoseond NLO studies at 800 nm were carried out using the Z-scan technique. The magnitude of third order nonlinearity was estimated to be ~4×10-13 esu. Solvent contribution to the nonlinearity was identified and estimated.

8071-46, Poster Session

Observation of the slow light propagation in saturable erbium doped fiber by side monitoring of fluorescence

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The erbium-doper fiber (EDF) is a very flexible and promising model medium for investigation of the slow/fast (and even the negative group velocity) light propagation in saturable optical materials. The experiments are performed in the spectral range 1480-1570 nm of absorption/gain of Er3+ ions using the input power of a sub-mW scale. Conventional experimental configuration allows one to observe, however, the input and the output pulse profiles only. Observation of the spatial changes in shape and delay of the light pulses through the fiber length can be investigated by the “destructive-method” only, by cutting the pieces of the fiber off. We report an original nondestructive technique to observe the spatial propagation of the pulses by means of the transient fluorescence excited by modulated light-pulses.

In the presented experiments we study the slow-light propagation in the EDF with saturable absorption (i.e. without optical pumping). The sinusoidally modulated power from the laser diode emitting at 1526 nm was coupled into the 3m long piece of a single mode erbium doped fiber. The fractional delay between the input and output light power profiles was measured with lock-in amplifier as a function of different experimental parameters such as frequency of modulation, average input power, and modulation depth. In addition to these traditional measurements, by the photodiode located at the fiber side, we observed the transient fluorescence signals excited by the propagating light pulses. Such measurements performed at locations separated by 0.5m gave us the complete spatial picture of the light pulses propagation.

The theoretical analysis was performed by means of a numerical

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simulation of the nonlinear pulse propagation in a saturable two-level medium. On the basis of the fluorescence measurements we were able to reconstruct how did the fractional delay and the amplitude of the propagating pulses change along the fiber.

8071-47, Poster Session

Optical and nonlinear optical studies of Ba0.5Sr0.5TiO3 thin films

K. V. Saravanan, K. C. J. Raju, M. G. Krishna, S. P. Tewari, S. Venugopal Rao, Univ. of Hyderabad (India)

Herein we present our detailed experimental results on the physical, linear, and nonlinear optical properties of rf sputtered Ba0.5Sr0.5TiO3 (BST) films deposited on MgO substrates at different deposition temperatures (Td), ranging from 500oC to 800oC. X-ray diffraction studies revealed that the films deposited at 500oC were amorphous in nature. The films deposited at 600oC were preferentially oriented along (111) direction whereas films deposited at 700oC and 800oC were oriented along (110) and (200) directions, respectively. Scanning Probe Microscopic studies showed that the surface of the BST5 films deposited at 500oC was smooth (RMSroughness = 0.7 nm) and the films deposited at 600oC had an RMSroughness value of ~8.7 nm which decreased to ~3.3 and ~2.2 nm for the films deposited at 700 and 800oC, respectively. The linear refractive index (n0) and optical band gap (Eg) determined from the transmission spectra indicated that n0 increased from 1.97 to 2.21 and Eg decreased from 4.2 to 3.7 eV with increase in Td from 500oC to 800oC. The nonlinear absorption studies were performed near 800 nm using ~2 ps and ~25 ps pulses with the Z-scan technique. The nonlinear absorption switched from reverse saturable absorption type in the films deposited at Td <600oC to three-photon absorption (3PA) in the films deposited at Td >600oC. The magnitude of the 3PA coefficient was estimated to be ~10^-21 cm3/W2. The variation of nonlinear coefficients with growth conditions is studied and explained.

8071-49, Poster Session

Investigation of the proton exchange phenomenon in Lithium Niobate crystal by means of investigation of the diffraction efficiency of a proton exchanged grating

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A grating structure is fabricated on the surface of a x-cut lithium niobate wafer by means of proton exchange technique in pure benzoic acid. After presenting theory of the diffraction from a phase binary grating, fabrication and experimental results are presented. To fabricate the grating, 1mm thick x-cut LiNbO3 wafers are coated first with 300nm thick Aluminum as a resistive mask in proton exchange process. A photoresist layer is then spin coated on Aluminum surface. Using a photomask, a grating pattern with 50 microns period is then transferred to photoresist layer. After development, the samples are put in 8g/lit KOH solution to remove Aluminum. The remaining resists then is removed and 25microns width strips of Aluminum pointing y axis of the crystal remain on LiNbO3 wafer surface. The wafer is then cut in 1cm by 2cm pieces, the strips pointing along the larger side. Different samples are then baked in pure Benzoic acid at T=239°C for different times from 5 to 45 minutes to perform PE process. The samples are then cleaned and the Aluminum mask is removed by KOH solution.

A laser source emitting at a wavelength of 532nm passes through a polarizer and diffracts from PE grating on lithium niobate samples. The diffraction pattern is captured by a CCD camera using a Fourier lens for ordinary and extraordinary polarizations.

By investigating the diffraction efficiency of the grating for different times of proton exchange process, optical path difference for proton exchanged regions is calculated. To estimate the proton exchange depth, d, the wafer with 45 minutes of baking, is cut and polished from one end and the polished area is inspected under a 400X microscope and d=2.1 micron is estimated for the proton exchange depth. the amount of change in refractive index is then estimated as 0.093 for extraordinary and 0.06 for ordinary polarizations using the fact that distribution of refractive index in proton exchanged region with benzoic acid is step-like.

To define the sign of refractive index changes, we try to couple laser light into the PE regions from one end. Since the PE regions are 25microns width strips, they can act as a waveguide if refractive index change is positive and they can not guide the laser light if refractive index change is negative. Experimental results show that the laser light with extraordinary polarization is coupled into PE regions but the laser light with ordinary polarization, is not. It means that the change in refractive index is positive for extraordinary polarization and negative for ordinary polarization.

By having the amount of change in refractive index and diffraction efficiency, the diffusion parameter is then estimated

8071-23, Session 7

Recent advances in the physics of spatial optical solitons

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We will discuss recent advances in the physics of spatial optical solitons and light localization, including self-trapping of light in periodic photonic structures and waveguide arrays, control of light diffraction and focusing in modulated waveguide arrays, spatial solitons and optical vortices in unbiased nematic liquid crystals, and plasmon focusing in tapered waveguides and the propagation of plasmon solitons.

8071-24, Session 7

Self-trapped beams: a fabrication technique for tri-dimensional integrated optics

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Spatial solitons are intriguing entities that have attracted a lot of interest over the past decades. Particularly, the versatility and ease of implementation of photorefractive solitons have been exploited for numerous fundamental demonstrations. In this presentation, spatial solitons and self-trapped beams are considered as a tool for realization of 3-D optical circuits. LiNBO3 is chosen as the host medium since it is a key material for photonic applications. Formation of self-trapped beams is described with special interest for the recently discovered so-called pyroliton relying on the pyroelectric effect for its formation. Properties of waveguides and 3-D integrated circuits induced by self-trapped beams are presented.

8071-25, Session 8

Scale-free optics and diffractionless waves in nanodisordered ferroelectrics

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Wavelength rigidly fixes diffraction that distorts waves during propagation, and poses fundamental limits to imaging, microscopy, and communication. This distortion can be avoided by using waveguides or nonlinearity to produce solitons. In both cases, however, diffraction is only compensated, so that the wavelength still imposes rigid laws on wave shape, size and soliton intensity. Nonlinearity, in turn, can introduce new spatial scales. In principle, if one is able to identify a nonlinearity that introduces an intensity-independent scale that cancels the wavelength, "scale-free" propagation can occur. In this regime, diffraction ceases, and waveforms will naturally propagate without distortion, forming solitons of any size and intensity, even arbitrarily low. Here we provide the first experimental evidence of scale-free optical propagation in supercooled Copper-doped KTN:Li,

a recently developed out-of-equilibrium ferroelectric. Working in the non-ergodic phase allows us to artificially enhanced and tune the nonlinearity: at a specific rapid cooling rate of the sample the generally negligible thermal diffusion scale of photoexcited electrons matches the micrometric wavelength scale, and scale-free optics emerges. We observe non-diffracting beams of arbitrary width and intensity, beam interaction, collision, spiraling, and scale-free modulation instability. We also demonstrate response programmability through thermal history, making, for example, the scale-free regime polarization dependent. We elaborate a theory of scale-free optics based on a photorefractive diffusion-driven nonlinearity for a nanodisordered dipolar glass and extend standard paraxial studies to the non-paraxial regime. In particular, we are able to formulate a non-paraxial scale-free soliton theory and predict propagating solutions with a width below the optical wavelength, opening the road to subwavelength imaging in the bulk. We provide preliminary experimental evidence of solutions that allow subwavelength propagation, and discuss schemes for the observation of images without evanescent waves. Our results demonstrate that diffraction can be canceled, and not merely compensated, in the paraxial and non-paraxial regime, thus leading to a completely new paradigm for ultra-resolved imaging and microscopy.

8071-26, Session 8

Photorefractivity of zirconium-doped lithium niobate crystals

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Some recent papers have shown that the photorefractivity of congruent lithium niobate (LN) crystals can be strongly reduced by doping the crystal with tetravalent ions, such as Hf [1-3], Zr [4]. Since a key role in the photorefractive process is played by the presence, in the congruent LN (cLN) crystal, of Li-sites occupied by Nb ions, the aim of doping is that of removing these native defects by incorporating the dopant ion at the Li-site in competition with NbLi . In this field it is customary to introduce the concept of a threshold concentration, defined as the minimum doping concentration required for strongly reducing photorefractivity. The interesting aspect is that, in the case of tetravalent ions, the threshold concentration for a substantial reduction of photorefractivity is much lower than the value of 5.5% found with divalent ions, such as Mg .

In this work we concentrate the attention on Zirconium-doped congruent LN crystals (hereafter indicated as Zr:LN). In order to set the ground for the utilization of these crystals in nonlinear wavelength-conversion devices, it is necessary to investigate in detail the dependence of the photorefractive properties of the doped crystals on the dopant concentration and on the incident power. The latter is a very important aspect, little studied in the literature concerning LN crystals. In our experiments the photorefractive effect is induced by a 532-nm laser beam linearly polarized along the c-axis, and is probed by a 633-nm beam. The birefringence variations have been measured, by using the Senarmont method and a phase-sensitive scheme, at intensity levels varying from 155 W/cm2 to 1800 W/cm2., in the Zr concentration range 0-3mol%. In order to investigate the photorefractive behavior at incident intensities even larger than those used in the Senarmont experiment, we have also utilized a qualitative approach based on the direct observation of the distortion of the light spot transmitted by the crystal. In presence of photorefractivity, when the laser intensity exceeds a certain value, the transmitted light spot becomes smeared and elongated along the c-axis. Our data show that, for the range of light intensities typically useful for nonlinear optical devices, the concentration of ZrO2 to be added to cLN in order to strongly reduce the photorefractive effect can be in the range 2.5-3mol%. Considering that the growth of large homogeneous Zr:LN crystals should be easier than for Mg:LN, and that electrical poling of these crystals has already been demonstrated [4], Zr-doped LN could represent a more convenient choice than Mg:LN for the realization of room-temperature wavelength converters.

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8071-27, Session 8

Observation of the optical peregrine soliton

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We report the first experimental observation of the optical Peregrine soliton, a novel class of nonlinear localized structure first predicted to exist over 25 years ago. Our results confirm the increasingly important role that experiments in optics play in providing insight into wider areas of nonlinear physics. In optics, the most well-known solitons are the hyperbolic secant envelope solitons of the nonlinear Schrodinger equation (NLSE), but the NLSE admits many other classes of localised structure, and there has been significant interest in soliton solutions existing upon a finite background. One particular structure of this type is the Peregrine soliton whose existence was predicted over 25 years ago but which surprisingly has never been the subject of any systematic experimental study and has never been observed in the original hydrodynamic environment in which it was first studied. The Peregrine soliton is of fundamental significance because it is a two dimensional soliton localised in both time and space, and because it defines the limit of a wide class of solutions to the NLSE. A weakly modulated CW field injected into an anomalous dispersive fiber described by the standard NLSE undergoes induced modulation instability where the modulation cycles of the field experience temporal compression and amplification. At the low-frequency limit of this process, the Peregrine soliton is excited, associated with a simple polynomial form for the field amplitude describing its two dimensional localisation. In this study, we implement experiments in optical fibre generating femtosecond pulses with strong temporal and spatial localization, and near-ideal temporal Peregrine soliton characteristics. In particular, we have excited the Peregrine soliton using two external cavity lasers around 1550 nm to create a weakly modulated CW signal injected into 900 m of highly nonlinear fiber. Experimental measurements using autocorrelation, spectral analysis and frequency-resolved optical gating (FROG) were used to measure the reshaping of the input field towards the solution predicted by Peregrine. In showing that Peregrine soliton characteristics appear with initial conditions that do not correspond to the mathematical ideal, our results may impact widely on studies of hydrodynamic wave instabilities where the Peregrine soliton is considered a freak wave prototype.

8071-28, Session 9

Second-harmonic generation and electro-optic modulation in thermally poled and unpoled twin-hole silica-glass optical fiber

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The second-order nonlinearity in poled optical fiber is promising for application to electro-optic (EO) modulation, second-harmonic generation (SHG), and frequency conversion. We thermally poled a twin-hole silica-glass fiber and studied SHG and EO modulation. The twin-hole fiber was similar to PANDA fiber except that the strain applying part was vacant. Metal electrode wires were inserted into the side holes. The typical poling condition was the voltage of 2.5 kV, the temperature of 300 °C, and the time for 40 min.

For SHG, we poled the fiber, removed wire electrodes, and measured the SHG using a linearly polarized Q-switched Nd:YAG laser. The measured SH power was proportional to the square of the fundamental power and was the highest for the polarization parallel to the poling electric field. Quasi phase matching was performed by periodic erasure of nonlinearity by irradiation with a KrF excimer laser through a silica mask patterned with a chromium stripe. Using an equivalent period of 41.4 micrometers, the SH power increased by a factor of 7. We also measured the SHG with poling without removing the electrodes. Although forward or reverse voltages up to 4.5 kV were applied, variation in the SHG power was negligible.

The SHG without poling was measured by applying the voltage to the metal electrodes during measurement. This corresponds to electric-field-induced second-harmonic (EFISH) generation. The SH power was proportional to the square of the applied voltage up to 4.5 kV, and the power was about 1/18 that of the poled SHG without quasi phase matching. This result was compared with that of P.G. Kazansky and V. Pruneri, Phys. Rev. Lett. 78 (1997) 2956.

For the experiment on EO modulation, twin-hole fiber with electrodes was inserted to a fiber-optic Mach-Zehnder interferometer. The effective fiber length was 2 cm. The AC modulation voltage with a DC bias voltage up to 4 kV was applied to the electrodes. The light source was 1.55-micron semiconductor-laser narrowband source. The output light of the interferometer was introduced to a photodiode, and the modulated AC signal was observed with an oscilloscope. Without poling, the modulation output was obtained only when a DC bias voltage was applied simultaneously. This shows that the refractive index change was proportional to the square of the applied voltage, which was based on the Kerr effect. After poling, a modulation output was obtained without any bias voltage, which shows the Pockels effect by the second-order nonlinearity. The measured EO coefficient was 0.06 pm/V. For the forward DC bias, the same polarity with the poling voltage, the modulation output increased with the applied bias voltage. For the reverse DC bias, the opposite polarity with the poling voltage, the modulation output showed the minimum for an applied bias voltage.

The mechanisms of the second-order nonlinearities and the other effects in the above SHG and EO modulation are discussed based on both the internal electric field by ion migration induced by poling and the external electric field.

8071-29, Session 9

Biphoton compression in standard optical fiber

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Generation of two-photon light with given spectral and temporal properties it's of great interest for quantum communication and quantum metrology applications. In particular, preparation of biphotons with ultra-narrow correlation time is a very important task. In a recent series of papers [1, 2], our group analyzed the production of two-photon wavepackets, by means of spontaneous parametric down conversion emission, in crystals with linearly chirped quasi-phase matching grating. Wavepackets present very broad spectra but a broad spectrum does not necessarily imply small correlation times, although the inverse is true. Indeed, the spectrum broadening induced by the grating is inhomogeneous; for this reason, the two-photon spectral amplitude presents a phase (a frequency chirp) that depends nonlinearly on the frequency. Hence, the two-photon wavepackets are not Fourier transform-limited.

As suggested in [3], the ideal way to make the wavepacket perfectly transform limited is to insert in the path of the biphotons a proper optical medium that compensates the non-linear part of the phase factor present in the spectral amplitude.

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In our work, we investigate the non-local temporal compression of the photons induced by the insertion of a standard optical fibre in the path of one of the two photons. We present and discuss systematic study of this phenomenon and some optimal situation where the full numerical calculation shows an effect that can be clearly observed with a realistic set-up. The study has open the way to the practical realization of this idea[4].

8071-30, Session 9

Quasi-phase-matched third harmonic generation in optical fibers using refractive-index gratings

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The purpose of this work is to demonstrate the quasi-phase-matching of third harmonic generation process in photonic crystal fibers using refractive-index gratings. We compare conversion efficiency calculated with analytical coupled modes theory and numerical approach employing the generalized nonlinear Schrödinger equation. We discuss the effect on conversion efficiency of several parameters including pump power, mode field diameter, glass nonlinearity and grating modulation depth. Moreover, we show that introducing the phase matching condition that takes into account the nonlinear contribution to propagation constants significantly increases the conversion efficiency by several orders of magnitude. Our results show not only that the grating must satisfy the nonlinear quasi-phase matching condition but also that we must take into account the modulation of the grating nonlinear parameters in order to reach the maximum conversion efficiency. For the optimum grating period in a standard single-mode optical fiber, the efficiency reaching 20% over the propagation distance of 45 cm can be achieved, whereas in fiber without grating the maximum efficiency is only 10-7. Nevertheless, we outline that even small detunings from the phase matching condition can be very destructive to the process. Finally, we study a possible way of further improvement of the efficiency through the application of a microstructured fiber with small mode area and high nonlinearity. Indeed, an increase of efficiency is expected by application of high power femtosecond pump pulses, which requires here a special fiber design matching the group velocity at pump and third harmonic frequencies to avoid the effect of pulse walk-off.

8071-31, Session 9

Photorefractive light scattering in nonlinear $LiNbO_3$ single crystals

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One of the most promising quantum and laser optics material is an optically nonlinear LiNbO3 (LN) single crystal [1]. Optically and structurally perfect LiNbO3 stoichiometric single crystals are used as materials for nonlinear laser mediums due to the periodically polarized domain nanostructures with plain confines as well as for holographic recording of information [3]. Due to the vide area of homogeneity on a phase diagram, and to many technological factors LN is a highly imperfect single crystal. Defects determine photorefractive effect (PE), accompanied by photorefractive light scattering (PRLS) in LN. Local changes of the refraction index (visible as a track) and crystal structure distortion happen in a photorefractive single crystal in the laser beam volume and in its proximity. So, a great amount of static microstructures could be generated in such a crystal under a visible laser beam radiation.

When irradiated by visible laser beam, PRLS shows itself as a three-layer speckle structure due to interference of direct and scattered laser radiation. The first and the brightest layer corresponds to the volume of the crystal run through by a laser beam. When the power is low or the time of laser effect is small, local micro- and nanostructures having modified physical parameters appear in the laser beam volume. When power or time of radiation rise, the structures flow together and become a solid track. The second layer is light scattered by micro points with laser induced changed refractive index. On pictures it is seen as the ring of bright points around the central spot of the first layer. The third layer is light scattered by fluctuations of crystal physical parameters. When observed dynamically it is seen as glimmer around the second layer and has no clearly seen points. But on the static picture these points could be registered as dull points scattering light.

All these structures have modified physical parameters (such as optical density, permittivity, etc.) and have a less ordered crystal structure than the surrounding structures of a single crystal.

Dynamic observation also reveals that the power transfers from the inner layers into the outer ones when the time or the power of radiation increase. At this the shape changes from the oval spot to the comet-shaped elongate speckle structure.

8071-32, Session 9

Rapid prototyping of color structures using 3D laser lithography

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Nature is colorful. Inspired by feathers, insects and plants, we try to produce brilliant colored surfaces, resulting from structures on the scale of the wavelength of the ambient light.

Employing 3D laser lithography based on two-photon- absorption, the structures are written into a photosensitive polymer. A highly intense pulsed laser in the near infrared is focused into a spot within the photosensitive material and moved along the confines of a selected structure. The material itself is transparent for the used wavelength, but within the laser's focal volume the probability of multi-photon absorption is strongly increased and leads to local polymerisation.

The produced structures look similar to stretched trees with varying heights; they exhibit lamellas of high index polymerised material surrounded by air. This index difference leads to diffraction and interference of light within a lamella, resulting in a wavelength-dependent reflectance and as a consequence to a colored surface. The observed colors display a strong brilliance and an excellent uniformity with respect to the observation angle.

This procedure could prove beneficial for prototyping of bionic structures and for a better understanding of their principles. Compared to pigments, the resulting colors are strong and long-lasting.

8071-33, Session 10

Finite element modelling of induced gratings in nonlinear optics

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In this paper, we present a multiharmonic model able to allow for general nonlinear optical media. As a particular example, two- and three-photon processes are considered here. The numerical model is based on the finite element method that allows to take into account the inhomogeneities of the refraction index due to the nonlinearities. It consists of several harmonic equations at various frequencies coupled via some nonlinear terms.

To simplify our model, the geometry is taken invariant along the z-axis and an appropriate principal axis for the susceptibility tensors is considered here together with a polarization of the electric field along the axis of invariance (the z-axis) in order to reduce the problem to a scalar two-dimensional one.

The numerical implementation is performed by a direct coding of the weak formulation of the three coupled partial differential equations (in fact, three sets of harmonic Maxwell equations respectively for the fundamental frequency and for the first and second harmonics). The discretization is performed with triangular finite elements. The incident field is imposed via a virtual antenna, a special numerical technique that we have specially designed for these nonlinear scattering problems. It turns the incident field to equivalent sources at a finite distance, even for incident plane waves, and allows the use of Perfectly Matched Layers for the total field.

As an illustration we propose a simple homogeneous uniform slab made of non-linear material (BBO) but illuminated by three plane waves in order to create an artificial periodic structure with a fictitious permittivity: the geometry of the system is an infinite slab, it is infinite along the x-axis i.e. the horizontal direction of the cross section. Made up of beta barium borate (BBO), it is illuminated by three plane waves, one with a normal incidence and two with a symmetric oblique incidence of 0.439 rad with respect to the normal. Harmonics are generated in the nonlinear medium. Due to the interferences of the different waves oscillating at the fundamental frequency, a structure (periodic along the x-axis and, therefore, equivalent to a diffraction grating or a finite photonic crystal) is induced in the cross section of the slab. This induced grating generates several orders for the fundamental frequency and for the higher harmonics.

This system exhibits a non trivial and quite complex behavior because of the induced diffraction grating. We show that the variation of the diffraction orders for the various harmonics do not vary monotonically with the amplitude of the incident waves.

8071-34, Session 10

Surface SHG as the method of remote control of dielectric mirrors quality

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One of the promising remote control methods of the optical surfaces quality is the method based on registration of radiation of the second harmonic (SH) generated on the surface of the analyzed sample.

This method is successfully used in microelectronics at fabricating multilayer semiconductor chips, it is also used for metal surfaces diagnostics, for investigation of superthin films with the thickness up to a monomolecular layer, in chemistry and biology.

The key advantage of the method is the absence of a signal from a bulk of a substrate material possessing the property of central symmetry where the SH generation is strictly forbidden. At the same time, the conditions of symmetry are broken near the surface and spatial inversion is no longer an operation of symmetry with respect to a normal to the surface. Thus, a surface layer of any material is always characterized by quadratic nonlinear susceptibility. Hence, a SH signal carries the data on the medium surface.

The value of quadratic nonlinear susceptibility on the surface of dielectric materials is several orders smaller as compared to semiconductors and metals. Nevertheless, our experiments showed that sensitivity of the method is quite sufficient for registration a SH signal from the surface of a dielectric mirror coating deposited on a glass substrate.

It is known that one of the problems in the LIGO project is degradation of the quality of a laser beam in interferometer resonators. Distortions of the radiation wave front that repeatedly passes through optical elements and reflects at the mirrors are related to accumulation of different types of contaminants on their surfaces.

A Ti:Sapphire laser system generating 80 fs pulses with the energy up to 140 uJ operating with the repetition rate of 3.6 kHz was used as a pumping radiation source. The output laser radiation was focused on the surface of the sample, so the intensity reached 0.45 TW/sq.cm.

We have studied the surface SH generation (SSHG) on a dielectric mirror when additional layers of a vacuum oil and PMMA were deposited on its surface. The oil was chosen as one of possible pollutants precipitating on mirror surfaces in the vacuum system of a LIGO interferometer during its long-term operation.

The experiment to study the effect of the thickness of additional surface layers of different artificial “pollutants” on the SH signal has been performed. The PMMA thickness of 40 nm and 400 nm was controlled in the process of spin coating a PMMA layer from a toluene solution. Measurements showed that a SH signal does not practically depend on the thickness of a deposited film but, however, it exceeds the signal from an uncoated clean surface of a dielectric mirror by several times.

Polarization properties of a reflected SH signal depending on polarization of pumping radiation were investigated. Also in experiments a signal was measured at different angles of pumping radiation incidence on the studied sample. Thus, optimal conditions for performing an experiment yielding maximal measurement sensitivity have been found.

8071-35, Session 10

PhoXonic architectures for tailoring the acousto-optic interaction

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Periodic media offer impressive opportunities to manipulate the transport of classical waves like light or sound. Elastic waves can scatter light through the so called acousto-optic interaction, which is widely used to control light in telecommunication systems. On the other hand, the radiation pressure of light can generate elastic waves through the elasto-optic interaction. Concurrent control of both light and sound through simultaneous photonic-phononic (often called phoxonic) band-gap structures is intended to advance our understanding as well as our ability to manipulate light with sound and vise versa. In particular co-localization of light and sound in phoxonic cavities could trigger non-linear multi-phonon absorption and emission processes and lead to enhanced acousto-optic interactions. In the present communication, we report on different phoxonic crystal architectures: simple one-dimensional multilayers, two-dimensional periodically patterned silicon slabs and three-dimensional metallodielectric crystals, aiming to provide optimum parameters for operation at telecom light and GHz sound. These structures can be subsequently used to design either phoxonic cavities and study the acousto-optic interaction of localized light and sound or phoxonic waveguides for tailored slow light-slow sound transport. As an example, we discuss the acousto-optic interaction in simple one-dimensional multilayer structures and study the enhanced modulation of light by acoustic waves in a phoxonic cavity. In this case, a consistent interpretation of the physics of the interaction can be deduced from the time evolution of the scattered optical field, during the excitation by an acoustic wave. We analyze the differences between resonant and non-resonant interacting modes and discuss the influence of dissipative losses, which are crucial in resonance phenomena and should be taken into account at least for GHz acoustic waves.

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8072A-01, Session 1

Recent advances in superconducting NbN single-photon detector developments

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The recent advances in the NbN superconducting single-photon detector (SSPD) development will be presented.

SSPD is a planar nanostructure patterned from 4-nm-thick NbN film deposited on sapphire substrate. The sensitive element of the SSPD is 100-nm-wide NbN strip. The device is operated at liquid helium temperature. Absorption of a photon leads to a local suppression of superconductivity producing subnanosecond-long voltage pulses. In infrared (at 1550 nm and longer wavelengths) SSPD outperforms avalanche photodiodes in terms of detection efficiency (DE), dark counts rate, maximum counting rate and timing jitter. Efficient single-mode fibre coupling of the SSPD enabled its usage in many applications ranging from single-photon sources research to quantum cryptography.

Recently several new improvements were introduced to the SSPD. The first one is the SSPD with photon number resolving capability (PNR-SSPD) [1]. This device realizes a spatial multiplexing of incident photons, i.e. instead of one long strip we make several meander-shaped strips covering together the same area of 10 μm x 10 μm and connected in parallel. Each strip has a serial planar resistor of 5 - 50Ω (depending on the number of strips we use) fabricated on the same chip with the detector. These resistors ensure uniform current distribution and prevent cascade switch of all the strips after photon absorption. The response magnitude of such a detector is proportional to the number of strips which become resistive simultaneously. That means the response is proportional to the number of simultaneously absorbed photons. We shall present photon-number resolution with detectors consisting of up to 11 parallel strips and high DE.

Another improvement to the SSPD is the increase of the photon absorption using a λ/4 microcavity integrated with the SSPD. Previously a fabrication of the mirror on top of the detector was reported [2]. In that design the SSPD could not be effectively coupled to optical fibres. The main problem was the deposition of the high quality superconducting film on the dielectric λ/4 layer of the cavity. We successfully resolved this problem and observed a resonant behaviour of the DE of our device.

And finally in our strive to increase the DE at longer wavelengths we fabricated SSPD with the strip almost twice narrower compared to the standard 100 nm. The motivation was to make the width of the strip closer to the diameter of the ``hot spot" that appears after photon absorption. To increase the response voltage we connected 50-nm-wide and 10-μm-long strips in parallel and utilized cascade switching mechanism [3]: absorption of a photon breaks the superconductivity in a strip leading to the bias current redistribution between other strips followed their cascade switching. In middle infrared (about 3 μm wavelength) these devices have DE several times higher compared to the traditional SSPDs.

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8072A-02, Session 1

Superconducting single photon detectors based on parallel NbN nanowires

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Superconducting single photon detectors (SSPD) based on ultrathin NbN nanowires are of significant current interest for long distance quantum optics applications due to their good efficiency, dark count rate and timing jitter at 1550 nm wavelength. Current SSPD research is focusing on the use of parallel nanowires for achieving pseudo photon number resolution, increasing the efficiency at longer wavelengths and increasing the area coverage. When increasing the SSPD area one must face both the problem of maintaining nanowire uniformity across large areas and also avoid the decrease in SSPD operation speed. Here we present how these problems can be overcome using parallel nanowires and show our results on SSPDs with area coverage up to 40 x 40 μm2 based on 100 nm wide ultrathin NbN nanostrips with a 40% filling factor. Using a standard SSPD operation we achieved a maximum count rate of 33 MHz which is faster than the standard meandered serial SSPDs. Furthermore, using an innovative operation procedure, that exploits the large signal amplitude of our parallel nanowire SSPDs, we could achieve 80 MHz operation. Due to the large area coverage we also identified a new operation region with two-photon sensitivity which we argue could be used to make a sampling photon number resolution SSPD. The increase in SSPD area coverage should open the way towards applications using multimode

fibers or irregular photon emitters.

8072A-03, Session 1

The performance of a versatile setup for superconducting nanowire single photon detectors

M. Keshavarz Akhlaghi, A. H. Majedi, Univ. of Waterloo (Canada)

We report on the performance of our new setup for testing Superconducting Nanowire Single Photon Detectors (SNSPDs). The optical cryostat consists of a dipstick that is firmly mounted on the edge of an optical table. It goes inside a liquid helium Dewar while not touching the body of the Dewar to achieve low-vibration operation with minimized cryogen consumption. A system of high vacuum chamber, radiation shields and cold widows is exploited to isolate the cold plate and SNSPD from unwanted heat loads and radiations. A temperature sensor, a heater, a capillary tube together with a roughing pump and a controller is used to adjust and monitor the operation temperature. A room temperature beam shaping and steering mechanism delivers the intensity and polarization controlled optical signals to the detector through free space optical access. The optical signals are generated by tuneable parametric down conversion of 1064nm femtosecond laser pulses in Periodically Poled Lithium Niobate. The electric response of the biased SNSPD after amplification stages can be monitored in real time on a fast oscilloscope or statistically on a programmable counter. We present our results on the performance of the various parts of the system. The achieved operation temperature range, its stability and also cryogen consumption rate is presented to elaborate the performance of the cryostat. We also present the results on the quantum efficiency and system quantum efficiency measurements in different operation temperatures and different excitation wavelengths. Furthermore, the dependency of the timing delay and timing jitter of the Niobium Nitride SNSPDs on biasing, operation temperature and excitation wavelengths are illustrated through a set of measured curves.

8072A-04, Session 1

Superconducting single photon detectors based on multiple cascade switches of parallel NbN nanowires

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Ultrathin NbN nanowires is the material of choice for superconducting single photon detectors (SSPD) due to the good efficiency, dark count rate and timing jitter at 1550 nm wavelength obtained. These performance parameters are achieved using nanowires a few nanometers thick and 100 nm wide patterned into a meander shape in order to achieve area coverage. The meander shape effectively makes the SSPD of a single very long nanowire in turn giving it a significant inductance which limits the maximum count rate of the detector. Recently, we demonstrated how one can exploit a cascade switch to the normal state of nanowires connected in parallel to significantly reduce the SSPD inductance and increase the signal amplitude. Here we present how one can configure SSPDs that uses multiple cascade switches to the normal state. We show how this principle can be used to expand the SSPD coverage area with a very limited increase in detector inductance with area. Finally we discuss our first results obtained with SSPD based on the multiple cascade switch principle, showing correct operation, increased operational bias range and increased signal pulse amplitudes.

8072A-05, Session 2

Silicon SPAD with near-infrared enhanced spectral response

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Single Photon Avalanche Diodes are nowadays the best choice for a large number of applications that require single photon resolution. They compare favorably with Photomultiplier Tubes thanks to the typical advantages of solid state devices and in terms of Photon Detection Efficiency (PDE). Last generations of thin SPADs developed at Politecnico di Milano showed great performances in terms of timing resolution (better than 35ps), dark count rate (less than 10cps for a 50µm-diameter device at -20°C) and afterpulsing (less than 2%); moreother, thanks to their planar fabrication process, they have been manufactured also in form of small arrays of detectors. However, most demanding applications require a further improvement in PDE, especially in the near infrared region.

The aim of this work is the development of a novel device able to match a red enhanced behaviour with all the winning features of the classical thin SPAD recalled above. In effect past efforts led to the realization of detectors able to achieve an excellent PDE but at cost of an unacceptable timing resolution and sacrificing the possibility to design arrays due to the use of a non planar technology.

Our goal was a PDE higher than 30% at a wavelength of 800nm. Starting from that, we designed a family of devices showing limited timing resolution worsening (about 100ps), the same dark counting rate levels of the classical SPAD and relatively low operating voltages (a breakdown voltage of about 100V and an overvoltage less than 20V).

A planar technology was used to make possible the design of arrays. The efficiency to be achieved sets the thickness of the depletion region, while other doping profile features are aimed at obtaining a suitable shaping of electric field. In particular the low operating voltage constraint is fulfilled by choosing an electric field profile characterized by two regions: a high field multiplication region where impact ionization takes place and a low field drift region aimed at collecting and accelerating the photo-generated carriers.

Device optimization has been carried out by using suitable models purposely developed. The final design resulted in a device with a drift region about 8µm-thick and a multiplication region about 2µm-thick. That has required the use of a suitable designed triple-epitaxial layer.

A major issue during the device development turned out to be the breakdown at the edges of the diode. Due to the higher overvoltage and to the thicker depletion region it is a more severe problem than in the classical thin SPAD. Biased guard rings ended up to be the solution that assures a proper detector operation.

In this paper we will discussed both the issues related to device design and to its experimental characterization.

8072A-06, Session 2

t-SPAD: a new red sensitive single photon counting module

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Applications that require to detect very low-light levels are usually performed with Single Photon Avalanche Diodes (SPADs) rather than photomultiplier tubes, because SPADs feature a much higher photon detection efficiency. If SPADs are combined with Time-Correlated Single Photon Counting (TCSPC) electronics for time-resolved data acquisition not only the detection efficiency is a crucial parameter for selecting a suited detector, but also the temporal resolution ("jitter") needs to be considered.

In this presentation we will show technical data and first application results from a new type of red sensitive single photon counting module ("t-SPAD"). The t-SPAD photon counting module combines Laser Components' ultra-low noise VLoK silicon avalanche photodiode with specially developed quenching and readout electronics from PicoQuant, targeted at timing applications, most prominently in the area of Single Molecule Spectroscopy (SMS). The t-SPAD features an extremely high photon detection efficiency of 75 % at 670 nm and can be used to detect single photons over the 400 nm to 1100 nm wavelength range. The timing jitter of the output of the t-SPAD can be as low as 350 ps, making it suitable for time-resolved fluorescence detection applications using TCSPC. We will show first application results including Fluorescence Lifetime Imaging (FLIM), Single Molecule Spectroscopy and Fluorescence Correlation Spectroscopy. First photon coincidence correlation measurements also show that the typical afterglow effect of SPADs is comparably low for these new SPADs.

8072A-08, Session 2

Floating field ring technique applied to enhance fill factor of silicon photomultiplier elementary cell

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A silicon photomultiplier (SiPM) is a matrix of Geiger-mode avalanche photodiodes (GM-APDs) connected in parallel in order to combine the photon counting capabilities of each of the microcells into a proportional light sensor. One of the main drawback in the SiPm is the low Photon Detection Efficiency(PDE) also due to the low geometrical fill factor of the microcells array.

This paper reports on the analysis and simulation of the single floating field ring technique, applied to the junction termination of the single cell of a Silicon Photomultiplier (SiPm). A floating guard ring is made along the border of the single microcell and it's not connected to the cathodic contact.

Even if the ring is not electrically connected to the main junction, it mitigates the variation of the electrical field at the main termination. In order to achieve the maximum effect of the ring, it is very important to place it at an optimal distance and it is further more important to locate it within the depletion width of the main junction. The effect of the junction-to-ring distance is analytically investigated by using cylindrical coordinates and an optimal distance is found. Finally the optimal width of the floating ring is also investigated. Results show that the single floating ring reduces the junction edge electric field by keeping constant the size of the microcell allowing, then, an improvement for the geometrical fill factor. This technique doesn't need a further technological step since it can be implemented by modifying the mask design of the main junction.

Results are supported by Sentaurus TCAD simulations.

8072A-09, Session 3

Development and construction of the photon counting receiver for the European laser time transfer space mission

I. Prochazka, J. Blazej, J. Kodet, Czech Technical Univ. in Prague (Czech Republic); J. Brinek, Czech Space Research Ctr. (Czech Republic)

We are presenting the work progress and recent results in the development and construction of the photon counting receiver, which is prepared for the European Laser Timing (ELT) experiment in space. ELT is an optical link prepared in the frame of the ESA mission "Atomic Clock Ensemble in Space" (ACES). The ultra short laser pulses will be used to synchronize the time scales ground to space with picosecond precision. To minimize the timing biases the photon counting concept of the space born receiver was selected. The requirements put on the photon counting receiver are quite challenging in terms of the long term detection delay stability, wide operation temperature range, extremely high background photon flux and others. Recently, the bread board version of the detector has been constructed and is under extensive test in our labs. The concept and construction will be presented along with the achieved device parameters.

8072A-10, Session 3

Photon counting receiver for the laser time transfer, optical design, and construction

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We are presenting the design of an input optics of the photon counting detector. This device is under construction in our lab, it will be used in the European Laser Time (ELT) transfer space project. The main goal was to design an input optics. The narrow bandwidth optical filter of bandwidth of 1nm centered at 532nm has to be used to reduce background photon flux. Such a filter has a narrow field of view, however the entire optics must have much larger field of view and must keep the detection timing delay, detection timing jitter and signal energy constant for different incident angles. To enlarge optics field of view in our design the front pupil consists from partially covered hemisphere, where its base is made of ground glass, which guarantees wide acceptance angle and the variable density optical coating controls the energy dependency on beam impacting angle. The goal was to reduce the ground-glass angle dependence and to compensate the decrease of energy with increased ground to satellite distance. The simulation and optics design will be presented. Recently, the bread board version of the detector has been constructed and is under extensive test in our labs.

8072A-11, Session 3

Photon counting altimeter and Lidar for air and spaceborne applications

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We are presenting the concept and preliminary design of modular multipurpose device for space segment: single photon counting laser altimeter, atmospheric Lidar, laser transponder and one way laser ranging receiver. For all the mentioned purposes, the same compact configuration of the device is appropriate. Overall estimated device weight should not exceed 5 kg with the power consumption below 10 W. The device will consists of three main parts, namely, receiver, transmitter and control and processing unit. As a transmitter a commercial solid state laser at 532 nm wavelength with 10 mW power will be used. The transmitter optics will have a diameter at most of 50 mm. The laser pulse width will be of hundreds of picoseconds order. For the laser altimeter and atmospheric Lidar application, the repetition rate of 10 kHz is planned in order to obtain sufficient number of data for a distance value computing. The receiver device will be composed of active quenched Single Photon Avalanche Diode module, tiny optics, and narrow-band optical filter. The core part of the control and processing unit including high precision timing unit is implemented using single FPGA chip. The preliminary device concept includes considerations on energy balance, and statistical algorithms to meet all the mentioned purposes will be presented. Recently, the bread board version of the device is under construction in our labs. The concept, construction, and timing results will be presented.

8072A-12, Session 3

Using pulse position modulation in SLR stations to transmit data to satellites

G. Kirchner, F. Koidl, D. Kucharski, Space Research Institute (Austria)

Satellite Laser Ranging (SLR) Stations determine distances to satellites by measuring the time-of-flight of short (10 ps to 100 ps) laser pulses, reflected from corner cube reflectors (CCR) on satellites. At present, laser repetition rates vary between 10 Hz and up to 2 kHz; SLR stations with higher repetition rates are planned.

At the Graz 2 kHz SLR station, we upgraded the software to modulate the - usually constant - interval between laser pulses; using such a Pulse Position Modulation (PPM) scheme, we successfully transmitted standard ASCII text files via a 4288 m distant CCR back to a Multi-Pixel Photon Counting (MPPC) module in our receiver telescope. With such a setup at any SLR station, and a suitable detector plus simple time tagging electronics at Low Earth Orbiting (LEO; < 1000 km) satellites, it is possible for any kHz SLR station to transmit data to satellites with a rate of up to 2 kB/s - even during standard SLR tracking.

As this technique is easy to implement and does not affect routine kHz SLR tracking, it can be applied to upload data to satellites, using the more than 30 available SLR stations around the world, and with higher data rates than some of the conventional microwave uplinks; using standard GSM - mobile phone - encoding techniques, it would allow also voice transmission.

8072A-13, Session 3

Fully integrated time-to-amplitude converter for multidimensional TCSPC applications

M. Crotti, I. Rech, M. Ghioni, I. Labanca, Politecnico di Milano (Italy)

Nowadays, the measurement technique of time correlated single photon counting (TCSPC) is increasingly widespread in a large number of fields, from medicine, to chemistry, to biology, and in a large number of applications such as single molecule fluorescence spectroscopy, fluorescence imaging, and laser scanning microscopy.

TCSPC measurements allow the analysis of very fast light waveforms with a resolution of few picoseconds and they basically consist in the revelation of a single photon and in the measurement of its arrival time within the period of a light signal; after the detection of many photons, it is possible to reconstruct a histogram which represents the probability distribution function of the photon within the period; the histogram corresponds to the intensity of the light signal.

Recently all the TCSPC systems are focused on single channel applications, and in order to fit the specifics of even more applications such as fluorescence lifetime imaging and diffuse optical tomography, the reduction of cost, area and dissipated power of the single chain is of utmost importance.

The most important section in the acquisition chain for TCSPC is the time measurement block, which must present a very high resolution and a very low differential nonlinearity (DNL) in order to be able to reconstruct the analyzed signal without introducing distortions;

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moreover to allow parallelization of a large number of converters, the development of a new kind of converter focused not only on the performance but also on the low cost and low area is necessary.

To meet all these specifications we have realized a fully integrated time to amplitude converter (TAC) in 0.35 μm Si Ge technology, with 45 ns full scale range and a total occupied area of 490x440 μm2.

Although the operating principle of the converter is extremely simple (a conversion capacitor is charged by a constant current; the voltage across the capacitor increases linearly with time and is proportional to the time interval between start and stop signals), the use of low jitter logic gates and of low noise analog circuits has allowed to obtain a constant and less than 50 ps full width half maximum (FWHM) time resolution.

For conversion times larger than 1 ns, the measured DNL is less than 4% peak to peak with a rms value of less than 0.1%.

The converter dead time, corresponding to the interval between the arrival of a stop signal and the instant when a new start signal can be accepted, is 60 ns. Therefore, the maximum conversion frequency is about 16 MHz. The converter presents a differential output voltage suitable for the differential input of modern ADCs. A differential voltage allows a better resolution, since all external common mode disturbances can be rejected; moreover, since the main contribution to dissipation is due to the differential output buffer, the power dissipated is almost independent of the conversion rate and less than 50 mW.

8072A-14, Session 4

Quantum optoelectronics by NbN superconducting nanowire single photon detector

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Superconducting Nanowire Single Photon Detectors (SNSPDs) have been proved to exhibit wide optical spectral responsivity from far Infra Red (IR) to visible wavelengths, detection speed in excess of hundreds of MHz, jitter timing as low as tens of picoseconds, and ultra-low dark count as lows as multi-Hz. SNSPD consists of low-temperature superconducting meandering nanowire typically made of NbN, Nb or NbTiN on top of a dielectric substrate such as MgO and Si.

I will report our activities on the analysis, simulation and characterization of the electrical and optical properties of two differently packaged SNSPD systems one based on deep-stick cooling system and the other based on small and compact cryostat. The DC current-voltage characteristics, as well as capacitance and nonlinear kinetic inductance measurements through RF scattering parameter measurements will be presented. By showing single photon optical detection at telecom wavelengths, i.e. 1310 nm and 1550 nm, I present our measurements of speed, jitter time, system quantum efficiency and dark count rates for these two systems. At the end, the single photon optoelectronic mixing by SNSPD will be shown where either CW or pulsed modulated single optical photon is mixed with a local RF signal. Optoelectronic mixing sensitive to the number of optical quanta will be discussed and its potential applications in quantum communication will be elaborated.

8072A-15, Session 4

Integrated superconducting nanowire detectors for quantum plasmonics

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We fabricate and implement superconducting single photon detectors in a range of quantum optics experiments. We follow several routes to boost the detection efficiency of superconducting nanowire detectors: integration into resonant cavities, implementation of plasmonic waveguides and coupling to planar waveguides. We illustrate the advantages of our detectors with measurements performed on single quantum dots emitting in the IR.

Integration of our detectors with plasmonic waveguides allows for all-on-chip quantum optics experiments where emitters, waveguides, beamsplitters and detectors can all be integrated to perform quantum plasmonics experiments at the single plasmon level. We demonstrate single plasmon detection enabling the operation of an integrated interferometer.

To access other detection ranges in the mid-IR, we have fabricated and tested detectors based on superconducting materials with lower gap. The operation of a NbSi detector will be presented and its advantages discussed.

We will also show that our detectors have potential applications beyond photon detection: single electron and single beta particle detection will be presented.

8072A-16, Session 4

Analysing non-classical photon statistics of quantum emitters with a single superconducting detector

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In the last decades different types of superconducting single-photon detectors (SSPDs) have been developed. For the so-called meandertype SSPDs the main advantages are a wide spectral range from the visible to the far IR, low dark count rates (<50Hz), and short dead times (<5ns).

For the investigation of a light source, in many cases its statistical properties are of interest. These are usually investigated by measuring the second order auto-correlation function of the electric field. This is mostly done by sending the light on a beamsplitter and measuring time differences between detection events at two detectors placed at the two outputs of the beam splitter (Hanbury-Brown and Twiss setup). However, for a detector with infinitesimal short dead times the second order correlation function could be determined directly by analysing the photon arrival times on a single detector.

There are different colour centers in diamond that can serve as single-photon emitters. Here, the emission from a single nitrogen vacancy (NV) center in a diamond nanocrystal was used. The size of the nanocrystal was around 25nm, which results in lifetimes of the excitations in the emitter of the order of 50ns, i.e. the characteristic times of the source exceed the detector dead time by one order of magnitude. Thus characteristics of the second order correlation function can be seen with a single meandertype SSPD.

In this paper we discuss our measurements of the non-classical photon statistics of the emission of a single NV-center in a diamond nanocrystal. We demonstrated that single-photon emission can be proved with a single SSPD.

8072A-17, Session 4

Spectral sensitivity of narrow strip NbN superconducting single-photon detector

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Superconducting single-photon detector (SSPD) is patterned from 4-nm-thick NbN film deposited on sapphire substrate as a 100-nm-wide strip. Due to its high detection efficiency (DE), low dark counts, and picosecond timing jitter SSPD has become a competitor to the InGaAs avalanche photodiodes at 1550 nm and longer wavelengths. Although the SSPD is operated at liquid helium temperature its efficient single-mode fibre coupling enabled its usage in many applications ranging from single-photon sources research to quantum cryptography.

In our strive to increase the DE at 1550 nm and longer wavelengths we developed and fabricated SSPD with the strip almost twice narrower compared to the standard 100 nm. To increase the voltage response of the device we utilized cascade switching mechanism [1]: we connected 50-nm-wide and 10-μm-long strips in parallel covering the area of 10 μm x 10 μm. Absorption of a photon breaks the superconductivity in a strip leading to the bias current redistribution between other strips followed their cascade switching. As the total current of all the strips about is 1~mA by the order of magnitude the response voltage of such an SSPD is several times higher compared to the traditional meander-shaped SSPDs.

In middle infrared (about 3 µm wavelength) these devices have DE several times higher compared to the traditional SSPDs.

[1] M. Ejrnaes et al. Appl. Phys. Lett. 91, 262509 (2007)

8072A-18, Session 4

Ferromagnet/superconductor bilayer nanostripes for optical-photon detection applications

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Superconducting single-photon detectors (SSPDs), based on meander-type, ultrathin NbN nanostripes, are currently becoming optical-photon detectors of choice, due to their unique physical characteristics in terms of the response time, quantum efficiency, photon-number and energy resolving capabilities. Here, we investigate the use of the proximity effect in weak-ferromagnet/superconductor nano-layered heterostructures with the aim of enhancing the SSPD performances. We have fabricated and characterized nanostripe devices formed by NbN films (thickness < 8 nm) covered by 3-to-10 nm thick NiCu alloy over-layers. Large detector areas have been obtained by pattering our NbN/NiCu bilayers as an "in-series" connection of multiple, parallel nanostripe meander-type blocks; thus, realizing a so-called "cascade switch mechanism." The above geometry allows a cascade transition of all blocks after the photon absorption and, hence, results in a large voltage output. We ha performed femtosecond pump-probe spectroscopy at cryogenic temperatures down to 4 K, using 100-fs-wide, 850-nm-wavelength optical pulses with 82-MHz repetition rate. This study shows that the proximity effect influences the dynamics of photo-induced, nonequilibrium quasiparticles by significantly decreasing their energy relaxation time. Simultaneously, the investigation of the NbN/NiCu transport properties [i.e., current vs. voltage (I-V), critical current density vs. temperature, and magnetic critical field measurements] demonstrates a very large increase (up to a factor 6) of the critical current density in the proximitized nanostructures, as compared to the pure NbN nanostripes. The observed enhancement is due to the increase of the vortex pinning and correspondingly results in large photo-response voltage signals of our NbN/NiCu photodetectors. Finally, the presence of current steps on the I-V characteristics of our detectors indicated formation of phase-slip centers in the 2-dimensional nanostripes and suggested the possibility of a new photon detection mechanism in such mesoscopic heterostructures.

8072A-07, Poster Session

Collection optimization of a tile shape radiation detector

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The light collection from a scintillator based radiation detector with a tile geometry shape configuration is an obstacle, especially if the light sensor can only be coupled to the scintillator narrow facet. This geometry shape characterized by a wide upper and lower surfaces and four narrow perimeter facets. The configuration enables to combine several plats into one joined sensor for unique detection applications.

The light emitted during the interaction of gamma photons with scintillation material is determined by the photon energy and the scintillation material properties; however the energy noise level depends on several key factors, where the light collection efficiency is a major one. Therefore, the final achievable noise level can be improved for the purpose of the detection of low energy gamma photons by optimizing the light collection efficiency.

This work presents results measured for several light collection configurations and comparison between the obtained noise levels. The detector designs were based on direct coupling of the light sensor to the scintillator and coupling through a wavelength shifter fiber.

The detector designed for this research consists of plastic scintillator, a fiber optic, electronics for signal amplification, reflectors and light sensor. Photomultiplier (PMT), which is the traditional selection for the light sensor was not selected for this setup because of its wide surface size that is not the best choice for coupling to the narrow facet scintillator. The light collection from a scintillator based radiation detector with a tile geometry shape configuration is an obstacle, especially if the light sensor can only be coupled to the scintillator narrow facet. This geometry shape characterized by a wide upper and lower surfaces and four narrow perimeter facets. The configuration enables to combine several plats into one joined sensor for unique detection applications.

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The detector's mechanical design was focused on designing and producing the optimal groove path and dimensions in the scintillator, and then mounting the wavelength shifter fiber into the groove. Another technical effort focused on coupling SiPM either directly to the scintillator or to the fiber and producing a robust and easy to install connection between the sensor, the electronic circuit and the packaging case.

The research optimization specifies steps that led to a final dramatic reduction in the noise level, based on the photo-coupling configurations, are described and discussed. The improvement was achieved by educated selection of the light sensor properties such as the Photon Detection Efficiency (PDE) versus the dynamic range and the biasing voltage, matching between the scintillation emission spectra and the light sensor Quantum Efficiency (QE) curve and the reflector designs (diffusive vs. specular).

8072A-19, Poster Session

A versatile all-digital time interval measuring system

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This paper describes a design and performance of a versatile all-digital time interval measuring system. The measurement method is based on an interpolation principle. In this principle the time interval is first roughly digitized by a coarse counter driven by a high stability reference clock and the fractions between the clock periods are measured by two Time-to-Digital Converter (TDC) chips TDC-GPX manufactured by Acam messelectronic. Control circuits allow programmable customization of the system to satisfy many applications such as laser range finding, event counting, or time-of-flight measurements in various physics experiments. The system has two reference clocks inputs and two independent channels for measuring start and stop events. Only one reference from 1 MHz to 10 MHz is required for the measurement. The second reference can be, for example, 1 PPS (Pulse per Second) signal from a GPS (Global Positioning System) to time tag events. Time intervals can be measured in two resolution modes corresponding to the resolution modes of the TDC-GPX chips. The resolution of each chip is software programmable and is PLL (Phase Locked Loop) stabilized against temperature and voltage variations. In high resolution mode the system can achieve a timing resolution better than 15 ps rms with up to 500 kHz repetition rate. In low resolution mode the system can achieve a resolution of 35 ps rms with a 9 MHz repetition rate. The time interval measurement range is up to 1 second. Short time intervals of up to 40μs can be measured down to 0 ps. The power consumption of the whole system is 18 W including an embedded computer board and an LCD (Liquid Crystal Display) screen. The embedded computer controls the whole system, collects and evaluates TDC data and provides a user interface. The system is implemented using commercially available components.

8072A-20, Poster Session

Ultrathin NbN films designed for superconducting single-photon detectors

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We present our research on fabrication and structural and transport characterization of ultrathin superconducting NbN layers deposited on single-crystal Al2O3 and Si substrates, as well as on SiO2 and Si3N4 films grown directly on Si wafers. Typically, superconducting single-photon detectors (SSPDs) are made of NbN nanostripes deposited and patterned on either sapphire or MgO single-crystal wafers. However, currently proposed new SSPD receivers directly integrated with advanced optoelectronic structures, such as distributed Bragg reflectors, optical waveguides, or plasmonic nano-antennas, require the new, optoelectronics-compatible substrates. Our ultrathin NbN films were grown using reactive RF magnetron sputtering. The films were deposited from a metallic Nb target in a mixture of nitrogen and argon gases on substrates maintained at the 700-850 oC temperature range. The thicknesses of studied NbN layers varied from 5 nm to 20 nm, in order to fully characterize their transmission and reflection coefficients in both infrared and visible ranges of optical radiation. The resulting NbN absorption coefficient dependence on the film thickness gave us the estimate of the expected intrinsic quantum efficiency of SSPDs patterned from the studied layers. We have also performed extensive morphology characterization of our films using ellipsometry, X-ray difraction (HRXRD), and atomic force microscopy (AFM) methods, and related the results (surface smoothness and structural properties) to the type of the substrate used for the film deposition. Finally, our transport measurements showed that even the 5-nm-thick NbN films had the superconducting critical temperature of 8 K. The thicker films had the critical temperature reaching up to 14 K.

Conference 8072B: Quantum Optics and Quantum Information Transfer and Processing

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8072B-21, Session 5

Quantum information science with integrated photonics

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Quantum information science has shown that harnessing quantum mechanical effects can dramatically improve performance for certain tasks in communication, computation and measurement. Of the various physical systems being pursued, single particles of light - photons - are often the logical choice. In addition to single photon sources and detectors, photonic quantum technologies will rely on sophisticated optical circuits involving high-visibility classical and quantum interference. Already a number of optical quantum circuits have been realized for quantum metrology, lithography, quantum logic gates, and other entangling circuits. However, these demonstrations have relied on large-scale (bulk) optical elements bolted to large optical tables, thereby making them inherently non-scalable and confining them to the research laboratory. In addition, many have required the design of sophisticated interferometers to achieve the sub-wavelength stability required for reliable operation. We report the implementation of quantum optic integrated circuits, which not only dramatically reduces the footprint of quantum circuits, but allows unprecedented stability and control of the optical path length; this reveals the possibility for realizing previously unfeasible large scale quantum circuits. We recently demonstrated silica on silicon circuits that implement key components for quantum information, including CNOT gates and the circuit at the basis of any single-qubit operation. These components show promising progresses toward fault tolerance operation. We used integrated waveguides to implement a circuit that performs a compiled version of Shor's quantum algorithm to factorize 15.

Here we report the demonstration of a circuit to herald entangled states useful for quantum metrology applications. We report demonstration of a silica-on-silcon waveguide device that is capable of heralding the two- and four-photon NOON states, as well as the four-photon entangled state useful in case of losses, dependent upon the input state and the setting of the internal phase.

Moreover we describe our most recent results on quantum walks of two correlated particles in arrays of coupled waveguides. When two photons are coupled into the waveguides, two photons correlations can be measured. Contrary to the evolution of single-particle quantum walks, these correlations cannot be simulated with precision with classical light as an input.

In order for linear optical quantum computing schemes to become practical an efficient source of single photons is required. We report on the implementation of a micro-fabricated single photon source based on diamond that allows high collection efficiency. By etching 5 micron diameter hemispherical solid immersion lenses into the surface of bulk diamond using a gallium focussed ion beam we measured a factor of 10 improvement in photon collection efficiency from a single NV-centre.

The results presented here, combined with efficient single photon detectors, will be the building block, for future demonstrations of quantum information with photons.

8072B-22, Session 5

Enhanced resolution in lossy phase estimation by optical parametric amplification

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The aim of quantum sensing is to develop quantum methods to extract the maximum amount of information from a system with minimal disturbance upon it. The employ of a quantum probe and entangled measurement schemes in order to estimate an unknown parameter can beat the shot noise limit imposed on the accuracy of the measurement. In optical phase estimation, an interferometric setup can be exploited to measure the phase shift introduced by a sample. In this context, the so-called N00N states, quantum mechanical superpositions of two terms where all the N photons are placed in either the signal or the reference arm, have been proposed to enhance the precision of the measurement up to the Heisenberg limit equal to 1/N. However, such class of states results to be extremely sensitive to losses, thus reducing their application in typical experimental conditions.

According to these considerations, a large research effort has been devoted in the last few years to design phase estimation protocols apt to work in a noisy environment. As a possible approach, the optimization of the probe states in presence of losses has been investigated in order to enhance the scaling of the phase resolution with the number of resources N. However, since the generation of these states becomes more complex when N increases, the implementation of this approach is limited in a few- photon regime.

In this context, we propose an alternative strategy that can be adopted to reduce the effect of losses in the resolution of phase estimation protocols. Our strategy exploits the insertion of an optical parametric amplifier in the transmission path of the probe after the interaction with the sample. The action of the amplifier, that is, the process of optimal phase covariant quantum cloning, is to broadcast the phase information codified in the probe state into a large number of particles. The obtained multiphoton states have been shown to exhibit a high resilience to losses and can be manipulated by exploiting a detection scheme which combines features of discrete and continuous variables. Such strategy allows to compensate for losses that occur after the amplification process at the transmission and detection stages. We have studied and experimentally tested the amplification interferometric measurement strategy with a single-photon probe, and by comparing the achieved sensitivity with and without the optical parametric amplifier. The enhancement obtained with our strategy in the phase estimation is much greater than one, and reaches the experimental value of 200 for high losses eta = 10^(-4).

These results open the perspective of generalizing the proposed strategy for alternative probe states with higher photon number, such as coherent states, by exploiting the property of the amplifier to broadcast the phase information into a larger number of particles. Further investigations will be devoted in this direction.

8072B-23, Session 5

Semiconductor Bragg reflection waveguides as source of entangled photon pairs: theory and experiments

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We show here that semiconductor Bragg reflection waveguides (BRW), which employs the process of spontaneous parametric down-conversion (SPDC), can serve as a tunable and highly efficient source of entangled photon pairs. The attractive features of AlxGa1-xAs and AlxGa1-xN waveguides are its large nonlinear coefficient, broad transparency window, low linear propagation loss and, importantly for the development of integrated quantum technologies, its readiness and mature technology for integration with laser sources and optical processing funcionalities in chips.

Phase-matching in the down-conversion process can be achieved when the pump mode propagates through Bragg reflection off periodic claddings, whereas the emitted down-converted photons propagate through total internal reflection. We demonstrate that we can control the dispersive properties of the waveguide modes and so the spectral properties (correlations and bandwidth) of the generated photons. In this manner, BRWs are capable to generate photon pairs with ultra-broad spectra in different polarizations and with the high degree of entanglement. On the contrary, BRWs based on AlxGa1-xN also allow the generation of quantum separable photon pairs (spectrally uncorrelated) with different or with equal spectral amplitudes. We also present waveguides designs that can be utilized as a source of nondegenerate photon pairs entangled in polarization.

We will show experimental results that confirm most of our theoretical proposals, and demonstrate the advantages of using semiconductor waveguides as a source of paired photons for quantum technology applications. Integration of the waveguide together with a Bragg reflection waveguide laser is the medium term goal that would provide a robust source of entangled photons.

8072B-24, Session 5

QED in cavities containing bounded inhomogeneous dielectric domains

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The role of quantum fluctuations in determining the behaviour of fabricated micro-structures is becoming increasingly important in a wide area of science and technology. Quantum interactions of matter with the electromagnetic field in renormalizable theories (QED) in an unbounded vacuum yield remarkably accurate predictions at the micro-scale. However macroscopic predictions directly from QED that are induced by the presence of bulk macroscopic matter and material interfaces can be made with far less confidence since they depend critically on both geometric and constitutive modelling on macroscopic scales. In particular the effect of quantum states of the electromagnetic field on the behavior of isolated closed material micro-domains of polarisable matter that exhibit dispersion remains an unsolved problem and an active area of current research.

A new mathematical and computational technique for calculating quantum vacuum expectation values of energy, momentum and angular momentum currents and densities associated with electromagnetic fields in bounded domains will be presented. This technique will be used to analyze the effects of quantum fluctuations of such fields in inhomogeneous and anisotropic dispersive media with particular attention devoted to the role of boundaries and interfaces between different media.

This offers a more straightforward approach that can accommodate in a natural way the many geometrical and constitutive properties that must be taken into account when dealing with anisotropic inhomogeneous magneto-electric media as well as contributions from macroscopic interface stresses (such as surface tension).

8072B-25, Session 6

High-fidelity noiseless amplification by photon addition and subtraction

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The possibility of amplifying quantum light states (although in a non-deterministic way) without introducing additional noise and without large distortions would be a precious tool for enhancing several quantum communication and quantum metrology tasks. For example, it could be used to distill and concentrate entanglement and could form part of a quantum repeater, or it could improve the performance of phase-estimation schemes and enable high-fidelity probabilistic cloning and discrimination of coherent states.

By precise quantum state engineering at the level of single photons, we have experimentally realized a novel concept of such a non-deterministic noiseless amplifier, and we have demonstrated its superior effective gain and high fidelity of operation when applied to coherent states of light of moderate amplitudes.

In its simplest realization, a fixed intensity gain of 4 is obtained by a sequence of single-photon addition and subtraction, experimentally implemented by means of conditional stimulated parametric down-conversion in a nonlinear crystal and conditional attenuation by a low-reflectivity beam-splitter. The application of this non-deterministic scheme for noiseless amplification has already shown that, for a given input coherent state amplitude, its effective gain and fidelity greatly outperform those of other existing approaches. In particular, the preservation of multi-photon contributions in the Fock base expansion of the amplified states is the main responsible for the exceptional performances of our method at larger amplitudes, where methods based on quantum scissors show limitations due to their abrupt state truncation. Compared to schemes based on the addition of thermal noise, our scheme also has the additional advantage of producing a pure amplified state at the output instead of a mixed one.

If a more complex interferometric scheme is adopted to produce a well-defined superposition of opposite sequences of photon addition and subtraction, a completely adjustable gain can be in principle obtained in the amplifier, and the same setup can be used to emulate Kerr nonlinearity.

8072B-26, Session 6

Polarization entangled state measurement on a chip

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Quantum optics represents an excellent experimental test bench for various novel concepts introduced within the framework of Quantum Information (QI) theory. Photons are the natural candidate for QI transmission since they are practically immune from decoherence and can be distributed over long distances, both in free-space and in low-loss optical fibres. Photons are also important for future quantum networks and are an obvious choice for optical sensing and metrology, finally, they are a promising candidate for computing. However, the current technology does not allow this transition for many practical limitations. Indeed, the development of increasingly

complex quantum optical schemes, realized in bulk optics suffers from severe limitations as far as stability, operation precision and physical size are concerned. Our goal is to take full advantage of the precious resource represented by the integrated waveguide technology in order to realize new complex quantum optical devices that would otherwise be simply unfeasible using largescale bulk optics alone. As a matter of fact there are many advantages in using integrated devices due to the small dimensions: the intrinsic stability and the potential scalability. Up to now many integrated photonic devices have been realized with lithographic techniques, a very successful technology, but its application is in general hard and restricted to the realization of bidimensional devices; moreover waveguides generated by lithographic methods present squared cross sections, whom transverse geometry doesn't allow the optimal propagation of gaussian modes. In the last years a new technique, based on the use of ultrashort laser pulses for the direct writing of photonics structures, has been demonstrated. This approach overcomes the main limitation of the strong asymmetry of the waveguide transverse profile: suitably controlling the writing operation, it is possible to obtain waveguides with a circular transverse profile, and this feature allows to support the propagation of gaussian modes. In order to implement quantum information protocols on laser written (LW) photonic circuits it's necessary to fabricate integrated devices able to guide and manipulate (efficiently) photons in any state of polarization, i.e polarization independent devices. Up to now, the adoption of polarization encoded qubits through LW circuits has not been carried out: indeed in all of the experiments performed on LW chips the polarization state of the incoming photons was fixed. On the contrary, here, for the first time, we exploit a polarization insensitive device realized with the LW technique to investigate interference effects with photons belonging to any state of polarization. Furthermore, we observed transmitted pairs of entangled photons without altering their superposition state and performed the singlet state projection, obtaining high visibilities and opening the way to the use of LW circuits for quantum information and communication processes.

8072B-27, Session 6

Prime number decomposition: the hyperbolic function, Gauss sums and multi-path interference

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Interference of probability amplitudes rather than addition of probabilities is the central lesson of quantum mechanics.

The double-slit experiment with de Broglie waves corresponding to a single neutron, the quantum eraser, or entangled particles in the Greenberger-Horne-Zeilinger state represent only three out of many striking manifestations of quantum interference.

The problem of factoring numbers using interference in a classical device, such as a Michelson interferometer, or in a quantum system, characterized by multi-photon quantum interference is part of the much broader theme of connecting the fields of quantum mechanics and number theory. Indeed, there exist many phenomena which point to an intimate relation between these two branches of science.

Most recently, the use of entanglement in a quantum system as a resource has played an important role in connection with the Shor algorithm to factor numbers. Here modular arithmetic meets quantum interference and has paved the way for the field of quantum information.

Indeed, it is the periodicity as expressed for example by the modular functions used in Shor method that is at the very heart of the algorithm.

Such functions are closely connected to Gauss sums which are central to analytic number theory. Therefore, it is not surprising that Gauss sums represent excellent tools to factor numbers.

Motivated by the power of interference and by the periodicity characterizing Gauss sums we use in the present paper interference in a multi-path Michelson interferometer to encode the hyperbolic function into a sequence of generalized curlicue functions. The locations of the central maxima of the resulting optical interferogram allow us to factor numbers as demonstrated by a recent experiment.

This method takes advantage of a remarkable scaling property characterizing the hyperbolic function and thereby the periodicity induced by such a function on the generalized curlicue interferograms. Such a property leads to a novel factoring algorithm which allows us to recognize the factors as the integer values corresponding to maxima by rescaling the measured periodicity for each number N to factorize. This is possible by measuring a number of interferograms scaling logarithmically with respect to the largest number to be factored.

Many avenues to extend this work offer themselves. We only allude to two: the arm lengths of the interferometer can be varied within a wide range as to implement different power laws in the generalized curlicue functions. Moreover, our considerations are not limited to classical optics. Indeed, many other waves such as matter waves, provided by atoms, electrons, molecules or neutrons can be put to use to factor numbers in a similar fashion. In general, any system where interference of many paths plays a role might serve as an implementation of the generalized curlicue functions.

Moreover, the connection between the Shor modular functions and Gauss sums at the core of this work serves as a motivation to extend such a parallelism between the two methods to the use of quantum interference in a binary representation in order to achieve a polynomial scaling in the number of resources.

8072B-28, Session 6

Non-equiprobable errors and the dynamics of Shor state verification

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We explore the explicit construction of Shor states in quantum error correction. We carry out detailed analyses of the effects of errors, paying special attention to the general case of non-equiprobable errors, i.e., the important and realistic situation in which the probabilities for sigma_x, sigma_y and sigma_z errors are not necessarily the same (sigma_x, sigma_y and sigma_z are the Pauli operators). We obtain exact analytical results for the case of a sufficiently small number of ancilla measurements, and obtain leading order terms for the general case. We calculate and analyze the density operators associated to the Shor states we construct.

8072B-29, Session 6

Quantum interference from a three-level ensemble of radiators dressed in the standing wave of cavity field

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The quantum interference in spontaneous emission process from a resonantly system of radiators (atoms, ions, polaritons, molecules) plays an important feature for quantum information and transmission. Such cooperative behavior can generate new effects connected with nonomogenity of the dressed field and the position of atoms localized in the cavity. Here it is investigated the dependence of quasi-energeticall levels on the atomic positions in the standing wave. As was observed the standing wave modulates the Stark splitting of the atomic levels. This splitting is directly proportional with the atoms localization and achieves the maximal value in the loops and minimal value in the nodes of standing wave. Thus, the frequency of the spontaneously emitted photons carries the information about the position of the atoms in the loops. In the case when the distance between the atoms is less than wave length of the dressed field the emitted photons are strongly correlated. As was observed, for large values of laser field intensity, the control of spontaneous emission is realized at two frequencies and atom-atom interaction process. The implementation in quantum processing of photon-bunching effect generated by two atoms dressed in the standing wave is discussed.

8072B-30, Poster Session

Locality and causality in quantum optical entanglement

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The reason for studying e.g. entangled photons arose from questions raised by Einstein regarding the completeness of quantum theory. Suppose that a pair of photons is produced in an entangled state. How to, physically, explain the paradox of the immediate statistical relation between distant measurements. Einstein supposed additional hidden parameters to restore locality and causality. However, Bell's theorem of entangled photon correlations and Hardy's paradox of measurement after mutual annihilation seemed to reject any possibility of a classical probabilistic explanation.

In the present contribution it will be demonstrated that classical

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probability theory is not as restricted as is commonly supposed. Measurement after mutual annihilation and immediate correlation measurement are mathematically related in classical set-measure theory.

As is known, classical Kolmogorovian probability theory is founded on the measured probability triple. Here the sample space is any non-empty set. The sigma-field is the set of all subsets of the sample space. The triple is completed with a probability measure, P.

To model the annihilation behavior we will inspect the numeral representations of von Neuman and of Zermelo. Apart from their common definition of zero and unity, the two numeral systems consist of disjoint sets. Hence, sets from the two systems can represent the fact that the photons cannot co-exist in Hardy's paradox. Let us take, von Neuman, and, Zermelo, numeral 3 to represent the annihilating photons. Both sets are disjoint.

Use of the monadic union operation on subsets of the mutually excluding numerals can produce non-zero probability.

The relevance for quantum optics is obvious. Mutually excluding photons that fire a measurement can be represented in classical probability. Likewise set-measure theory is able to explain Bell's correlation. This seems to imply that photons really contain Einstein's extra parameters. Optics seems an attractive possibility for studying extra parameters because entangled photons are relatively easy to make

8072B-33, Poster Session

The role of measurement and random coins in the recurrence property of discrete timed quantum walks

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In the literature of random walks, the question of recurrence is an important issue. The number measuring the recurrence probability of the random walker is called the Pólya-number. In the spirit of random walks, an analogous concept was developed in quantum informatics: the quantum walks. Recurrence is again studied, leading to different results, characterized by a different Pólya-number associated to each walk than in the corresponding classical cases. One of the most important distinguishing trait is the higher number of parameters, more degrees of freedom leading to a more populous family of possible walks.

The present study aims at further broadening the scale, focusing mainly on the one dimensional case, introducing possible generalizations (some already existing in the literature, and some new), and examining the effects from the viewpoint of recurrence. We have two main directions. The first one is to include the projective measurement in the process of the walk itself, making the time evolution non-unitary.

The starting point of this approach is making a full position-measurement at each step. This case fully destructs the interference of possible paths, essentially reducing the quantum walk to a classical walk, but it places the classical walker on a graph instead of a line. A construction for the graph is given.

We continue with considering a notion of weaker measurement, asking not for the position of the walker, but only if it is in a certain position or not? Aiming for the recurrence, we choose this to be the starting position of the walker. The basis of this case is already studied, under the name of absorbing boundaries. The introduction of this process lowers the Pólya-number below one, making transient walks possible in one dimension (whereas in the normal QW, it is always recurrent) [1]. Additionally, in the two dimensional case, a related property is observed: the measurement extinguishes localization.

After introducing the measurement scheme, we change the way it is taking part in the process. We make the measurement not in every step, but in every nth step, periodically, or with 1/n probability, randomly. The Pólya-number is further diminished, we find that the original Pólya-number provides an upper limit.

The preceding process takes only those steps into account, when there is a measurement happening. We can include the steps during the unitary parts of the process, between the measurements. A mixed definition of the Pólya-number is given to account for all the possible paths.

The second approach is to introduce a random environment. The coin operator governing the motion of the walker is selected from a one-parameter family of operators randomly, and differently for every position (but fixed at the beginning). We observe that the introduction of this kind of a random environment leaves the Pólya-number unchanged.

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8072B-34, Poster Session

Propagation of light in optically modified atomic media

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Coherent preparation of an atomic medium by a laser light can lead to modifications of its optical properties characterized by the frequency dependent electric susceptibility. It is thus possible to influence a light pulse propagation in such a medium.

As the basis of the theory we consider the atomic dynamics and the optical response of the medium to a continuous-wave laser. I will examine this phenomenon using a -type model of atoms. Further I will study an extension of this model by introducing another weak microwave field to our system. At the end we will present the results based on [1] where the situation is analyzed in which the amplitude of this additional field is stronger and the corresponding interaction cannot be considered perturbatively. The most important effect that I examine is the Electromagnetically Induced Transparency (EIT). The idea is to apply to a medium two optical fields to create an atomic coherence which makes an initially opaque sample transparent for resonant radiation. The EIT is accompanied by modifications of a group velocity of a laser pulse and can be used to obtain "slow" and "stopped" light.

I will show how optical properties of an atomic system using perturbative approach are modified due to coherent interactions with laser light. I will consider a medium of three-level atoms interacting with two laser beams in the -type configuration [2]. Although such a model is very simple, one can find the media in nature whose level structure can be modeled by such a system. This gives us the possibility of modifications of dispersive properties of a medium which results in the phenomenon of the electromagnetically induced transparency. I will discuss modifications of EIT introduced by an additional interaction with a microwave field that couples lower states of a Λ system. I will also examine how opacity of a medium is dependent on the relative phase of applied fields and its possible applications. Another problem I will consider is quantification of group velocity of a probing laser beam and how to interprete group velocity when we at a time modify detunings of additional field and a probing field.

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8072B-35, Poster Session

SROP and DROP spectra with alkali atomic vapor cell and applications

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Two schemes of Doppler-free high-resolution velocity-selective optical-pumping (VSOP) atomic spectroscopy, called single-resonance optical pumping (SROP) and double-resonance optical pumping (DROP), are performed in room-temperature cesium and rubidium vapor cells. SROP and DROP signals actually indicate the variation of the zero-velocity atom population of one hyperfine fold of ground state, and this population variation is due to velocity-selective optical pumping from

one hyperfine fold of ground state to another via one-photon excitation or cascade two-photon excitation and thereafter decay processes. In SROP and DROP schemes, the probe laser is usually frequency locked to a cycling transition, and SROP and DROP spectra often have a flat background and higher signal-to-noise ratio (SNR). Therefore, SROP and DROP schemes are very useful for many applications, for example, measurement of dressed state splitting, laser frequency stabilization and frequency standard, precision measurement of atomic hyperfine splitting and so on.

1). While pumping laser passed through cesium vapor cell is scanned across cesium D1 or D2 lines, SROP spectra are obtained by monitoring the transmission of probe laser (also served as coupling laser) which is locked to 133Cs 6S1/2 (F=4) - 6P3/2 (F'=5) cycling transition in D2 line. As an application, SROP scheme is employed to measure the dressed-state splitting of 133Cs 6S1/2 (F=4) ground state with cesium vapor cell, even if the dressed-state splitting is much smaller than the Doppler broadening at room temperature. But normally the dressed-state splitting of atomic ground state only can be detected with laser-cooled atomic sample.

2). If a ladder-type atomic system has large spontaneous emission rates, absorption signal of probe laser which is used to approach a transition between two excited states has poor SNR and wide linewidth. DROP scheme can remarkably improve SNR of spectroscopic signal of a transition between atomic excited states. With 87Rb 5S1/2 (F=2) - 5P3/2 (F'=3) - 4D3/2 ladder-type system, DROP spectra are obtained and compared with conventional optical-optical double-resonance (OODR) spectra. Influence of the alignment of the pump and probe laser beams (co-propagating (CP) and counter-propagating (CTP) configurations) on DROP spectra are discussed. Thanks to electromagnetically-induced transparency (EIT) in ladder-type atomic system with the CTP configuration, DROP spectra with high-SNR and much narrower linewidth for 87Rb 5P3/2 (F'=3) - 4D3/2 transitions around 1529nm are achieved with rubidium vapor cell. As an application, a 1529-nm diode laser's frequency is preliminarily stabilized via DROP scheme in our experiment. Also the results of laser frequency stabilization via CP-DROP, CTP-DROP and OODR schemes are compared, and clearly CTP-DROP scheme greatly improves the frequency stability, which is significant in optical telecommunication field for correction of the communication channels in dense wavelength-division-multiplexing (DWDM) system.

8072B-36, Poster Session

Analysis of dynamic and static characteristics of InGaAs/GaAs self-assembled quantum dot lasers

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We have solved the rate equations for InGaAs/GaAs self-assembled quantum-dot laser considering homogeneous and inhomogeneous broadening of optical gain numerically using fourth-order Runge-Kutta method. Dynamic-characteristics are analyzed; relaxation oscillation frequency, modulation bandwidth, and turn-on delay improve as injection current increases. With enhancing of the full width at half maximum (FWHM) of homogeneous broadening, threshold current and turn-on delay increase, because of elevating of central group density of states. Simulation results of static-characteristics show that slope-efficiency increases as the FWHM of homogeneous broadening heightens due to enhancing of central group carriers. Exceeding of the FWHM of homogeneous broadening from FWHM of inhomogeneous broadening results in degradation of slope-efficiency and static-characteristics because empty DOS increas. Nonlinearity appears in light-current characteristics at a special interval from ratio of FWHM of homogeneous broadening to FWHM of inhomogeneous broadening. Differential gain decreases as initial relaxation time and recombination times heighten. Consequently, relaxation oscillation frequency and modulation bandwidth decline.

8072B-37, Poster Session

Quantum public-key cryptosystem with two indistinguishable quantum states

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We introduce two indistinguishable quantum states which have trapdoor property to distinguish them. The generation of the two quantum states and a quantum public-key encryption scheme based on them are presented. The security of this quantum public-key encryption scheme is shown to be unconditionally secure.

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8073A-01, Session 1

EUV detectors based on AlGaN-on-Si Schottky photodiodes

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Photodetectors designed for the Extreme Ultraviolet (EUV) range with the Aluminum Gallium Nitride (AlGaN) active layer are reported. AlGaN layers were grown by Molecular Beam Epitaxy (MBE) on Si(111) wafers. Different device structures were designed and fabricated, including single pixel detectors and focal plane arrays. Sensitivity in different configurations was demonstrated, including front- and backside illumination. The latter was possible after applying a dedicated integration scheme, where the detector chips were connected to custom-design Si-based readouts. High density In bump arrays (10 and 20 µm pixel-to-pixel pitch) were used as interconnects and the chips were bonded using the flip-chip bonding technique. In order to eliminate radiation absorption in silicon in the backside illumination configuration, the substrate was removed using SF6-based Reactive Ion Etching (RIE), leaving submicron-thin membranes (approximately 400 nm) of the AlGaN active layer suspended on top of the interconnect arrays. Optoelectrical characterization was performed using different light sources. First, a 150-W Xe lamp was used with filters for wavelengths between 200 and 400 nm to determine the cut-off wavelength. As expected from the Al concentration in the active layer (40% AlGaN), the cut-off wavelength of the detectors was 280 nm with the rejection ratio of the visible radiation above 3 orders of magnitude, proving the intrinsic visible and solar blindness. The devices were characterized also in the synchrotron beamlines, confirming the cut-off wavelength and providing spectral measurements down to the EUV range. Spectral responsivity and quantum efficiency values were extracted from the measurements to enable comparison with the state-of-the-art photodetectors.

8073A-02, Session 1

2D CMOS image sensors for the rapid acquisition of optically modulated and multi-parametric images

N. S. Johnston, R. A. Light, M. Somekh, J. Zhang, M. Pitter, The Univ. of Nottingham (United Kingdom)

Many imaging techniques require highly sensitive optical systems including detectors capable of measuring extremely small fluctuations in the detected incident light. Such systems use a modulated light source (at frequencies up to 100's of kHz) in combination with optics that induce a change in the amplitude and/or phase of the modulation in response to changes in the sample being imaged. These signals are usually demodulated using a point detector and a lock-in amplifier. However, this technique is not suitable for the fast acquisition of 2D images.

Using a modified active pixel sensor architecture, cameras with resolutions up to 256 x 256 pixels which are capable of demodulating optical signals with frequencies up to 1 MHz and have been designed and fabricated. Each demodulation pixel consists of a photodiode, a reset switch, four independently controlled shutter switches and four supplementary well-boosting capacitances that improve both linearity and signal to noise ratio. The reset and shutter switches are implemented with 5 V thick oxide transistors to maximize the dynamic range of the sensor. Demodulation is achieved by rapidly acquiring four images at 90 degree intervals of the modulation period, then applying simple post processing to extract the modulation amplitude, phase, and DC level of the optical signal. The camera outputs 16 parallel analogue channels and can deliver total pixel rates of up to 160 Mega pixels per second. A bespoke 12-bit 16-channel acquisition system for use with these cameras is currently in development.

In imaging systems where demodulation is not necessary, the camera can be clocked to behave as a conventional DC camera capable of taking four images with independent exposure periods allowing for advanced multi-parametric imaging.

8073A-03, Session 1

CMOS lock-in optical sensor for parallel detection in pump-probe systems

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In pump-probe type experiments the signal of interest is often a very small fraction of the overall light intensity reaching the detector, approaching as little as one part in one million. This is beyond the capabilities of conventional cameras due to both the necessarily high light intensity at the detector and limited dynamic range. To overcome these problems, phase-sensitive or lock-in detection with a single photodiode detector is generally used. In phase-sensitive detection, the pump beam is modulated with a chopper and the probe beam is captured with a photodiode that is connected to a lock-in amplifier running from the same reference as the chopper. Modulating in this way moves the signal away from drift, 1/f and other low frequency sources of noise, as well as providing very narrowband detection.

This setup provides very sensitive detection, but is slow if imaging or spectroscopy are to be carried out. The image sensor we have developed is a linear array detector fabricated in a standard CMOS technology that can perform shot-noise limited lock-in detection in up to 256 parallel channels. Each pixel has four independent wells, which allow phase-sensitive detection to be carried out. The depth of each well is massively increased by the addition of supplementary capacitance to reduce the effect of optical shot noise. In addition, the size of the wells can be controlled on a per-pixel basis. This allows the gain of the sensor to be matched to the incident light intensity, so that the effect of read-out noise can be minimised for regions of the image that have relatively low levels of intensity.

The array can reduce the number of dimensions that need to be sequentially scanned and so greatly speed up acquisition or images and spectra. Results demonstrating spatial and spectral parallelism in pump-probe experiments are presented where the a.c. amplitude to background ratio approaches 1 part in one million.

8073A-05, Session 1

Challenging design and development of Ma_Miss, a miniaturised spectrometric instrument for Mars sub-soil analysis

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This paper describes Ma_Miss (Mars Multispectral Imager for Subsurface Studies), the miniaturised instrument for spectrometric and stratigraphic analysis of sub-soil developed by SELEX Galileo in ESA ExoMars mission context. The Ma_Miss experiment is coordinated by the Principal Investigator A. Coradini (IFSI-INAF, Rome) and is funded by the Italian Space Agency (ASI).

The exploration of Mars requires a detailed in-situ investigation of the Martian surface and sub-surface. Determining the composition of the Martian subsoil will provide a direct indication of the steps through

which the sample material evolved through geological timescales.

Ma_Miss is an instrument fully integrated in the Drill system (developed by SELEX Galileo) hosted by Rover operating on Mars surface; Ma_Miss illuminates the wall of the drill borehole and acquires its reflectance signal in the Visible and Infrared (0.4-2.2 micron) range, analyzes it through a miniaturised spectrometer (21nm spectral resolution), and transmits the digital data to the Rover.

The instrument is very challenging because it is the first time that a Rover will land on Mars for drilling beneath the surface (down to 2 meters) with a Drill-embedded optical instrument to observe the wall of the hole.

The modular architecture of Ma_Miss includes the optical head, the illumination system, and the optical fibre that brings the signal from the optical head up to the spectrometer. The multispectral images are acquired through a sapphire window placed on the lateral wall of the Drill.

The innovative instrument concept was driven by several key needs, related to challenging scientific requirements and extreme environmental constraints. Implementation of the concept has required a deep interdisciplinary concurrent development in order to solve critical aspects of engineering and manufacturing, covering miniaturised monolithic optics and novel concept for fiberoptic connectors capable to automatically mate/de-mate during the robotic assembly of the Drill elements on Mars.

The originality of Ma_Miss is multi-fold. A key innovative point is the design and manufacturing process of miniaturised optics. The monolithic optical system introduces valuable simplification in integration and alignment; moreover providing intrinsic athermalisation. The optical head consists of 7 mirrors realised in two monolithic elements accounting a total weight of 11 grams. A couple of mirrors are contiguous but with different curvature radius, thus requiring a special algorithms for the machining tool. A further point of originality is related to the integration of the fiberoptic link inside the modular Drill elements requiring an ad-hoc fiberoptic connector type.

8073A-06, Session 1

Preliminary tests of commercial imagers for nano-satellite attitude determination

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Star cameras represent a well-known class of attitude determination sensors. At this time, they achieve excellent accuracy within arc-seconds. However their size, mass, power, and cost make current commercial versions unacceptable for use on nano-satellites. Here, the concept of developing a small star camera with very modest accuracy requirements for future nanosatellite missions is studied. A small commercial cmos sensor with minimal commercial optics is presented. The cmos imager has an active array area of 5.7 x 4.3 mm, with a focal length of 6 mm and an aperture ratio of 1.4. This camera's field-of-view is approximately 50 x 40 degrees and can capture stars of magnitudes smaller than 3 with acquisition times of 100 ms.

The accuracy of attitude determination methods using data collected by this camera was tested by taking photos of the night sky under terrestrial conditions. The fixed camera attitude was determined using offline image processing and star field attitude determination algorithms. Preliminary attitude accuracy results were determined and they are presented.

8073A-07, Session 1

Study on infrared small target detection technology under complex background

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Small target detection and tracking in infrared (IR) image sequences has been an important part in many military or civil fields such as video supervision, precision guidance and human-computer interfaces. As is well known, an infrared human image is obtained by inducing thermal radiation from a human body, and it can provide information that a visible image does not have. However, the background of infrared target is usually contaminated by unknown noise and the contrast between the target and the background is very low. Moreover, we always need to detect the target in the far distance which determines that the target is very small. Hence, developing infrared small target detection algorithm is still a great challenge.

Nowadays, different algorithms have been proposed for infrared target detection. However, under complex backgrounds, such as clutter, varying illumination, and occlusion, the traditional detection method often loses the real infrared small target. To cope with these problems, in this paper we have researched on the traditional infrared small target detection methods, summarized the advantages and disadvantages of these algorithms. On the basis of the analysis of these methods, according to the characteristics of the small target in infrared images, we propose an improved detection algorithm to enhance the detection performance. The experimental results show that, compared with the traditional algorithm, the presented method greatly improves the accuracy and effectiveness of infrared target detection under complex scenes, and the results are satisfactory.

8073A-08, Session 2

Novel optical fibre based architectures for chemical and biological sensing

T. M. Monro, The Univ. of Adelaide (Australia)

No abstract available

8073A-09, Session 2

Cascaded optical fibre long period and Bragg gratings for strain and temperature cross-sensitivities compensation in refractive index measurements

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The measurement of the analytes concentration in biological fluids is a very important task in biomedical applications. A very used technique consists of the detection of fluorescent markers chemically bound to recognition elements. In contrast the so called label-free techniques make it possible to measure directly the analyte concentration, for example detecting the refractive index changes of the chemical/ biochemical layer. Examples of label-free techniques are surface plasmon resonance, interferometric configurations, and recently optical resonating structures. Within the optical approach, optical fibre long period gratings (LPG) have been recently proposed for chemical and biochemical sensing. LPGs are characterized by a grating period in the range of hundreds of micrometres giving rise to the coupling between the fundamental core mode and a discrete set of forward-propagating cladding modes. The specific coupling between the modes verifying the phase-matching condition generates in the transmission spectrum a series of attenuation bands centred at discrete wavelengths. The resonance wavelength of the coupled cladding mode depends on the external (environmental) refractive index of the medium surrounding the fibre. These sensors have high sensitivity to the external refractive index, in addition to all the other benefits offered by optical fibre sensors. However, LPGs show great sensitivity not only to the external refractive index, but also to temperature, strain and fibre bending. The influence of these parameters can be critical when the refractive index changes are very low, as generally occurs whenever the measurement is carried out for chemical/biochemical sensing.

The present paper describes the design and characterization of a hybrid configuration which consists of a Long Period Grating (LPG) and a Fibre Bragg Grating (FBG) written on the same optical fibre. A thermo-stabilized flow cell of relatively low volume (tens of μL) together with an accurate temperature measurement system were developed. The FBG, the thermostatic flow-cell, and the temperature

measurement system were used to introduce feedback signals to reduce to a minimum the interferences coming from temperature and strain changes. The proposed system was tested on fluids of different refractive index.

8073A-10, Session 2

Multiple fiber Bragg grating sensor network with a rapid response and wide spectral dynamic range using code division multiple access

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Fiber Bragg grating(FBG) sensor networks have been intensively researched due to their novel characteristics such as electromagnetic interference immunity, multiplexing capability, and high sensitivity. For the implementation of FBG sensor network, wavelength division multiplexing(WDM) and time division multiplexing(TDM) technologies was adopted for its interrogating many optical sensors. In particular, WDM technology can be easily employed to multiplex and interrogate FBG sensor array due to a simple configuration and high resolution; however, the number of FBG sensors which can be accommodated in sensor array is limited by the spectral bandwidth of optical broadband source and spectral dynamic range of each sensor. On the other hand, the TDM technique can extremely expand the number of sensor regardless of spectral bandwidth because the FBG sensors have same center wavelength. However, it suffers from a reduced sensor output power due to low reflectivity of FBG sensor.

In this paper, we propose and demonstrated the FBG sensor network based on code division multiple access(CDMA) with a rapid response and wide spectral dynamic range. The CDMA method is based on the correlation technique to separate individual reflected sensor signal from a multiplexed signal. Thus, it constantly collects information from sensor array by using the pseudo noise(PN) code instead of optical single pulse so that it shows more rapid scanning rate than TDM method.

The reflected semiconductor optical amplifier (RSOA) as a light source was directly modulated by the generated PN code which has a code length of 127(27-1) at 800.1MHz. The modulated optical signal is amplified by using erbium doped fiber amplifier(EDFA) and goes through FBG sensors via circulator. In this experiment, three FBGs which have the different center wavelength and same reflectivity were used for measuring strain and temperature sensitivity. The center wavelengths of each sensor were 1549.2, 1550.9, and 1552.5nm, respectively, and the reflectivity of each sensor was 99.8%. When the modulated optical signal experienced FBG sensor array, the optical signal which was consistent with center wavelength of FBGs is reflected and added from each sensors. The added signal goes into dispersion compensating fiber(DCF) as a dispersion medium which has a fiber dispersion of -680ps/nm. By using the DCF, the time difference between each sensors were increase. After through the DCF, the optical signal is converted into electrical signal by using photodetector(PD). For separate individual reflected sensor signal, the correlation method was used. Specially, we used sliding correlation method in this experience. A sliding correlation method simply facilitates continuous monitoring without considering time delay among the reflected signals by using the two same codes with slightly different frequencies. The autocorrelation peaks, created when two PN codes are well-matched, are shifted in left side as the temperature applied to each sensor is increased. The temperature and strain sensitivity was measured using time shift of sensor. The proposed method improves the code interference by using wavelength to time conversion scheme using DCF. And it also has advantages such as a large number of sensors, continuously measuring individual sensors, and decreasing the complexity of the sensor network.

8073A-11, Session 2

Fiber laser FBG sensor system by using a spectrometer demodulation

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We constructed a FBG sensor demodulator by using a modified FD-OCT (Fourier domain optical coherence tomography) setup, which was designed for the 3-dimensional optical biopsy. The basic optical configuration is the same with that of the FD-OCT except the signal processing of the PD array outputs. In this sensor system, we locate the peaks in the reflection spectra and trace the variations of the peak positions which convey the measurand information. The large number of the PD array pixels and the fast signal processing for the 3-dimensional real-time imaging enabled a very efficient FBG sensor interrogation without the need of severe alteration of the optical configuration. To obtain enough signal-to-noise ratios for fast and high-resolution measurements, a fast wavelength-scanning fiber laser was constructed and used as a light source. The scanning frequency of the wavelength-tuned laser was over 1 kHz and more, which was fast enough for most of the temperature measuring and even some vibration analysis in electric power systems monitoring applications. The high output power and the multiplexing capacity of the sensor system are very suited for the quasi-distributed power system's integrity monitoring over a large area. The most desirable feature of this demodulation is the measurement linearity. By the wavelength-spatial transform of the volume holographic spectrometer, the nonlinearity of the wavelength-tuning filter is removed, resulting in the linear output regardless of the nonlinear action of the filter. In addition, the effect of the uneven light source power profile is compensated by referencing the spectrometer output profile. We applied this sensor system to monitor the transformer temperatures to alarm abnormal temperature variations and avoid possible power failures, which demonstrated good feasibility.

8073A-12, Session 2

Detection of biochemical reaction and DNA hybridization using a planar Bragg grating sensor

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The detection of biomolecules and biochemical reactions is very important in the Pharmaceutical and Chemical Industry. Both, determination of different concentrations and the tracing/surveillance of biochemical reactions in real time are of fundamental importance. In this respect, e.g., the detection and hybridization of DNA plays a significant role in modern life sciences.

We report on the usability of a silica on silicon based planar Bragg-grating (PBG) evanescent field sensor as a biosensor. Typical biochemical reactions such as the binding between Biotin (vitamin H) and Streptavidin can be traced in real time on the sensor surface. For this application, Biotin was attached to the silanized surface of the planar Bragg-grating sensor followed by the immobilization of Streptavidin with a concentration of 7.5 nM, 15 nM and 30 nM, respectively. To proof the capability of a real time monitoring with the refractive index sensor, the biochemical reaction was interrupted several times by applying a phosphate buffered saline solution showing a quasi instantaneous spectral response of the PBG sensor.

In addition, applying the same bio-functionalized sensor as described above we have investigated the detection of DNA hybridization. For this purpose, biotinylated single stranded DNA was linked to the sensor surface via Streptavidin. Using this functionalized PBG sensor surface, the DNA hybridization of unlabeled complementary single stranded DNA with a concentration of 5 μM can be observed.

8073A-13, Session 2

Optical fibers with conductive polymers like novel sensor structures

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Conducting polymers have been systematically studied during last two decades and the range of potential uses covers simple and cheep microelectronic parts, electrochromic devices, electromagnetic shielding, analytical separations, marker particles and sensors.

Anyway the topical research field still expands to new directions. Nanocomposites conducting polymer/phyllosilicate, sometimes referred as conducting polymer/clay, (further CP/phyllosilicate) represents one of the new fields in novel materials design, emerging in last several years.

Novel nanomaterials will provide new functions with potential utilization in many fields of applied materials research and industry. These materials form the basis of latest patterns of distributed temperature, electrical fields, biological activity sensing elements and sensors of extremely small currents. At the present time their potentially unique properties are irreplaceable by others sensing elements.

Silicate nanocomposites and hybrid organo-inorganic nanostructures with organic dyes embody fluorescence in VIS in agreement with initial experiments. This fluorescence is influenced by transmitted electric current in case of the conductive nanofilms and outer field for non - conducting nanostructures.

There are several possibilities for creation of sensing elements. In our experiments we have used two connected optical fibers. Each optical connector has been covered with thin film of silicate and hybrid organo-inorganic layer with dyes. We found out that two spectral windows exist in transmission measurement. The first window was temperature independent; the second one was strong dependent. It means that such connector coupling can be used both for data transmission and for sensing purposes. Data transmission requires temperature independent spectral window, temperature dependent spectral window is used as a temperature sensor. Both systems can operate at the same time.

Another possibility for sensor element preparation is usage of tapered optical fiber. We have used standard single mode fiber SMF 28e. We removed the acrylate coating and prepared tapered part of optical fiber. This part we have covered with conductive polymers and we measured fluorescence response induced with light passing through optical fiber.

Results from spectral measurements of transmitted light passing through connector coupling in dependence with temperature create the first part. Spectral range of measurement is from 380 nm to 1060 nm. The second part of results creates data from fluorescence measurements and their changes with temperature and composed influences like electric field, magnetic field and temperature together.

8073A-14, Session 3

Designing plasmonic nanostructures for SERS-based biosensing

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Surface-enhanced Raman spectroscopy (SERS) has been immerged as a powerful analytical and sensing tool for use in many important areas such as biomedical diagnostics, environment monitoring, food safety and security because of its molecular identification of specimens. Although hundreds of SERS papers are published each year, SERS has not been successfully transitioned from the research laboratory to practical use. The limited acceptance of SERS for routine analytical techniques is largely due to the lack of suitable SERS substrates that can produce reproducible detection signals for reliable quantitative analysis. Recently we developed a novel quais-3D gold plasmonic nanostructure composed of physically separate nanoholes in the top gold thin film and gold nanodisk at the well bottoms. Unlike most previous SERS substrates of random gold or silver nanoclusters (particles, rods, shells, etc.), these SERS substrates are fabricated via nanofabrications and offer many advantages. The precisely fabricated and rational designed nanostructures allow us to conduct the fundamental studies in order to understand the Raman enhancement mechanisms to the optical and plasmonic properties of metallic nanostructures using experimental and theoretical approaches. Based on the knowledge gained from the fundamental studies, we developed new SERS-active substrates optimized for high sensitivity of different size analytes (pathogens, virus, proteins, and chemicals). These unique SERS-active substrates were integrated with microfluidic systems for real-time in-situ detection of chemical and biological agents with molecular identities.

8073A-15, Session 3

Waveguide-integrated SPR sensing on an all-organic platform

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Optical and optoelectronical components and devices based on organic materials offer a wealth of possibilities in terms of integration, miniaturization and low-cost fabrication for relevant applications, notwithstanding a performance that may fall somewhat short of that of conventional systems. In this context we report on progress towards the combination of surface plasmon resonance (SPR) sensing with a monolithically integrated optical sensor platform based on organic materials, including an organic light emitting diode, an optical polymer waveguide and an organic photo diode. Several according components have been developed and demonstrated recently [e.g., B. Lamprecht et al., phys. stat. sol. (rrl) 2, 266 (2008); E. Kraker et al., Appl. Phys. Lett. 92, 033302 (2008); E. Kraker et al., Thin Solid Films 518, 1214 (2009); B. Lamprecht et al., phys. stat. sol. (rrl) 4, 157 (2010)] and exemplarily applied to fluorescence lifetime detection.

Aiming at multianalyte performance we add SPR to this platform, which enables the label-free detection of a wide range of analytes. The SPR detection scheme is based on a gold surface sustaining a surface plasmon (SP) mode which reacts sensitively to analyte-induced refractive index changes. For the integration we apply a 50 nm thick gold film onto the polymer waveguide and add a high-index overlayer for efficient light/SP coupling [H. Ditlbacher et al., Opt. Express 16, 10455 (2008)], while maintaining high SPR sensitivity. We will report the sensing performance of a multimode waveguide system and platforms relying on broadband optical excitation. While less sensitive than standard SPR in absolute terms, waveguide-integrated SPR can provide parallel detection for chemical and biological analysis with overall footprints in the millimetre range.

8073A-16, Session 3

SPRi biochip: impact of new immobilization chemistry

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Biomolecules electro-addressing based on the diazonium electro-reduction is a recent technology, taking advantage of the electrochemical grafting possibilities of aryl diazonium residues. The reaction sequence involved: (i) (i) the diazotation of an arylamine in the presence of NaNO2 and HCl giving an aryl-diazonium, (ii) this latter is electro-reduced to an aryl radical which (iii) reacts with the electrode material surface. The radical generated attacks the surface and forms a C-X bond, X being the electrode material. This technique of derivatization was already demonstrated on a wide range of conducting materials such as carbon, carbon nanotubes, silicon, metals and diamond. In most cases, the electrochemical addressing was performed in organic solvent (acetonitrile), and the modified electrodes were subsequently grafted with the interesting molecules.

The use of this reaction was first described on carbon material surface, and was applied to the indirect covalent immobilization of an enzyme. A glassy carbon electrode surface was functionalized by the electro-reduction of 4-acetic-phenyl-diazonium, leading to a 4-phenyl-acetic layer. Then a chemical covalent grafting of the glucose oxidase was performed to generate a glucose sensitive electrode. Diazotation reaction on an aniline derivative was also used to create a biotin layer, electro-addressed at a screen-printed carbon electrode surface. An aniline-biotin residue was diazotated and subsequently electro-grafted on the electrode surface, providing a covalent anchoring point for streptavidin.

During the last four years, our team has developed a real one-step electro-addressing immobilization strategy using aryl-diazonium modified biomolecules. Biomolecules are first chemically functionalized with an aniline derivative and this latter is diazotated in the presence of a NaNO2 acidic solution. The produced diazonium function is then subsequently involved in the electro-reduction reaction, leading to the grafting of the biomolecules at the working electrode surface. Cyclic-voltammetry and X-ray photoelectron spectroscopy were used to characterize the grafting and suggested that a diazonium monolayer was deposited.

This unique electro-addressing procedure onto conducting material was proven to be efficient for the immobilization of biomolecules as different as antibodies, oligonucleotides and enzymes. An adaptation of the technique was published in 2007 based on the modification of biomolecules with already diazotated derivatives. The obtained bio-analytical systems were based on the immobilization of antibodies, oligonucleotide and enzyme and exhibited interesting performances.

In the present study, an up-to-date overview of the developments of the technology for Surface Plasmon Resonance imaging (SPRi) biochips' preparation will be presented, onto both Biacore and Genoptics/HORIBA ® platforms. A two-step procedure based on the electro-grafting of aryl diazonium bearing a carboxylic acid function followed by a carbodiimide activation of the modified surface will be described. This activated surface, used for the immobilization of various proteins, will be compared to classical SPRi activation chemistries based either on thioctic acid self assembled monolayer (SAM) or dextran grafting.

8073A-17, Session 3

Analytical study on sensitivity enhancement of the angularly integrated long range surface plasmon sensor

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Recently long range surface plasmon (LRSP) become very popular approach for sensitive monitoring of the refractive index changes in cover medium since it is a leaky wave that penetrates many microns. LRSP mode(s) can be excited by either nanostructuring the sensor layer(s) or adding buffer layer(s). When a dielectric buffer layer(s) is introduced under metallic layer that creates a close symmetric condition on layer formation, excitation of symmetric and anti-symmetric TE and TM modes including the LRSP mode is possible at the same time. These modes appear in reflectance as resonance dips. Better sensitivity of an surface Plasmon(SP) sensor can be simply described as longer shifts on angular or spectral location(s) of very narrow resonance dip(s) when there is a small amount of the refractive index change in cover on the surface of the sensor. Therefore, very small changes on the cover RI can generate measurable signals with a more sensitive sensor. Sensitivity can be maximized by optimizing the design parameters such as wavelength of the incident light, thicknesses and optical properties of the sensor's layers. Here we present an analytical study on sensitivity enhancement of angularly integrated LRSP sensor that consists of prism, Teflon(buffer) and gold layers that create a close symmetric transducer structure. The effects of the sensor design parameters on the angular ($S\theta$) and intrinsic ($IS\theta$) sensitivities are studied for the cover RI from 1.33 to 1.37. The $S\theta$ and $IS\theta$ calculations for TM mode are conducted for wavelengths from visible (500 nm) to near IR (1000 nm). The best $S\theta$ and $IS\theta$ values for our RI variation range are 246 deg RIU-1 and 251 RIU-1 at λ=1000 nm respectively but for different thickness combinations of gold and Teflon layers supported by a BK7 triangular prism. The LRSP sensor's $IS\theta$ sensitivity is better than prism-teflon-gold LRSP sensors published in the literature. Also comparisons of results from the sensor's response to a thin biolayer formation with the commercial sensors (Surface plasmon enhanced fluorescence spectroscopy-SPFS and BIAcore) indicate that LRSP approach based on symmetric layers' formation is not capable for precise monitoring of a thin layer(s) of molecular formations. Investigation of prism's design parameters such as shape and material also shows that using lower RI material with a triangular shape improves the sensitivity. Even though optimization of the sensor's design parameters for a high precision measurements of the bulk refractive index is feasible, the LRSP sensor is not a practical solution for monitoring adsorption/desorption of a very thin (/mono) layer of molecules on the surface with a high sensitivity. Yet it can become quite useful to probe for changes at bacterial and cellular levels.

8073A-18, Session 3

Plasmon nanoparticles for optical biosensing

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Plasmon nanoparticles for optical biosensing

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Metal nanoparticles exhibit a large potential for the development of innovative and cost-effective sensing devices. They fulfill key requirements for biosensors such as the potential for miniaturization as well as for high parallelization, and they are compatible with the molecular world for the required biofunctionalization approaches. Their optical properties based on the localized surface plasmon resonance (LSPR) are well adjustable from the UV- to the infrared spectral range using chemical synthesis. Due to the strong influence of the surrounding dielectrics on the resonant properties these particles offer a high potential for sensing of minimal changes in the surrounding media. Additionally, plasmon nanoparticles can induce a local field-enhancement and so a signal amplification such as for fluorescence or Raman-spectroscopy. In general, plasmon nanoparticles are well suited as label or as transducer for different optical detection techniques.

The talk will give an overview about recent developments in this field, and will present different sensing strategies at single particle or ensemble level and based on planar or fiber-based systems aiming for ultrasensitive point-of care applications in bioanalytics.

8073A-19, Session 3

Optical biosensor based on localized surface plasmons on a nanoparticle array

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The past decade has witnessed an increasing effort toward application of localized surface plasmons (LSP) on metallic nanostructures in optical biosensing. In spite of that, LSPR biosensing data are still rather limited and there is a lack of comparison of performance of LSP-based biosensors with the established optical biosensors, for instance, surface plasmon resonance (SPR) biosensors employing propagating surface plasmons.

In this paper we report a novel LSP-based biosensor and perform a side-by-side comparison of its performance with a conventional SPR imaging sensor. The LSP sensing structure comprises an array of rectangular nanoparticles (nanorods). Gold nanoparticles are fabricated on indium-tin-oxide (ITO) covered glass substrates by electron beam lithography. Nine sensing arrays of 110 nm × 40 nm × 30 nm nanoparticles with a periodicity of 250 nm × 250 nm are prepared on each sensor chip. The nanoparticle arrays are optimized to exhibit an extinction peak in near infrared region. Sensor chip is illuminated with a narrowband infrared light with a central wavelength of 750 nm and changes in the intensity of reflected light at all sensing arrays are monitored by a CCD camera. The conventional SPR imaging sensor used for comparison utilizes an SPR chip coated with a uniform 50 nm thick gold layer. The sensor chip is illuminated through a coupling prism with the collimated narrowband infrared light in the attenuated total reflection configuration. Changes in the intensity of reflected light are measured by a CCD camera. An array of sensing channels is prepared on the sensor surface by means of microspotting. The used configuration of the conventional SPR imaging sensor allows resolving refractive index changes as small as 2E-7 refractive index units (RIU).

Both the LSP-based sensor and SPR sensor are evaluated in a model biosensing experiment in which hybridization of short oligonucleotides is investigated. Both sensors are functionalized with thiolated DNA probes anchored to the metallic surface. Multichannel detection of different concentrations of complementary oligonucleotides is carried out with both the biosensors. Performance of the two biosensors is compared in terms of saturation sensor response, binding rate kinetics of the sensor response, noise of the sensor response and detection limit. Detection of oligonucleotides at concentrations down to 100 pM is successfully demonstrated with both the biosensors. This limit of detection is comparable with the detection limits achieved with the best conventional SPR biosensors.

8073A-20, Session 3

Enhanced sensitivity of localized surface plasmon resonance biosensor by phase interrogation

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We proposed an innovative phase interrogation method for localized surface plasmon resonance (LSPR) detection. To our knowledge, this is the first demonstration of LSPR biosensor by phase interrogation.

LSPR is realized as the plasmonic resonance within confined metal nanoparticle. Nanoparticle couples the light by means of a non-radiative inter-band absorption, and a scattering from surface plasmon oscillation, the total contribution is the optical extinction of nanoparticles. Due to the variety of resonance types, LSPR is extensively studied in the field of biological sensing, imaging, and medical therapeutics. Generally, LSPR is probed by optical intensity variation of continuous wavelength, such as UV-Vis spectroscopy, Fourier transform infrared spectroscopy (FTIR), and dark-field microscopy. In other words, it is probed by wavelength interrogation. LSPR sensitivity probed by this method is ranged from several tens nm/RIU to less than 1000nm/RIU depending on the nanostructure and metal species, which at least an order of magnitude less than conventional SPR biosensor in wavelength interrogation. It is known that for conventional SPR biosensor, phase interrogation owns the superior sensing ability than other three interrogations (i.e. angular, wavelength, and intensity) because of a drastic phase jump at resonance, and we believe that LSPR sensitivity can be further enhanced by using phase interrogation.

In this work, an innovative common-path phase interrogation system is applied for LSPR detection. Phase difference in our home-made system is simply extracted through the correlation of optical intensity under different polarization without any heterodyne optical modulator or piezoelectric transducer, and thus low down the cost and complexity in optical setup. In addition, signal-to-noise ratio is substantially reduced since the signal wave and reference wave share the common path. Based on our system, sensing resolution of conventional SPR is up to 9.08 × 10-7 RIU. In our preliminary results, Au nanoparticle array with 235nm in length and 55nm in thickness fabricated by electron beam lithography were under test. From the FTIR measurement, LSPR resolution of Au nanoparticle array is 1.74 × 10–4 RIU; from the home-made phase-SPR system, LSPR resolution of Au nanoparticle array is 1.97×10-5 RIU. LSPR sensitivity in phase interrogation is around one order of magnitude enhanced than wavelength interrogation, and can be further enhanced by modulating geometry of nanostructure

In conclusion, we demonstrated that LSPR can not only be probed by wavelength interrogation, sensitivity can be further enhanced by phase interrogation. Moreover, the home-made phase-SPR system provides a simple setup, high sensitivity, and low cost platform for LSPR detection, which extend the application of LSPR by phase interrogation.

8073A-21, Session 4

New optical reference standard in the field of biology: interrogation of micro-resonator based biosensor with a phase sensitive-optical low coherence interferometer

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Since there is a lack of reference standard in the biological domain to measure very low concentration of molecules, the French National Metrology Institute (LNE) has decided to develop a new optical reference technique for bio-sensing applications. An association of a micro-resonator based biosensor with a Phase Sensitive-Optical Low Coherence Interferometer (PS-OLCI) is proposed.

The PS-OLCI's setup includes two Michelson interferometers: one using a low-coherent and the other a coherent light source. The interferometer with the broadband light source enables to interrogate the sensor, and the coherent interferometer using a HeNe laser allows the measured interferogram to be sampled with equally spaced and well-calibrated steps, thus enabling to perform Fourier transform. Therefore PS-OLCI allows to get information in the spatial domain, on the spatial transmissivity, as well as in the spectral domain i.e. to spectral transmissivity and above all to the phase as a function of the wavelength, in opposition to commercial device which only gives information in the spatial domain.

The proposed optical sensor is a polymeric micro-resonator made of a bus waveguide vertically coupled to a ring or racetrack waveguide for single mode operation. The ring waveguide surface will be functionalized in order to attach target molecules for specific detection and will be included in an opto-fluidic cell in which the solution to be characterized will flow. The micro-resonator and the micro-fluidic cell will be mounted on a thermostatic holder to control the temperature in order to stabilize the solution to be characterized. Also the conformational change of the molecules depending on temperature will be observed. The aim of the association bio-micro-resonator-OLCI is to detect very low concentration of molecules and to see the evolution of molecules with time and temperature.

As the light travels several time into the micro-resonator, the signal is stored; and thanks to the phase of optical signal given by the PS-OLCI, we expect that this association PS-OLCI-micro-resonator will provide relevant information on the molecules: concentrations with sensitivity <1 pg/mm², real-time investigation of the kinetics of specific molecules on time scale <100 ms. Thus, this novel technique will be complementary to other techniques such as Surface Plasmon Resonance (SPR), Dual Polarization Interferometry (DPI), etc., or to the micro-resonator interrogation technique based on the measurement of the spectral transmittance with a tunable laser.

In this paper, we will present the biosensor as well as the optical interrogation technique that we are proposing. We will show our first measurements results and indicate our future works to improve the performances of the technique under development.

8073A-22, Session 4

Single-mode integrated optical waveguides for spectroscopy of molecular sub-monolayers

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Single-mode integrated optical waveguides is a highly sensitive technique for investigation of surface-adsorbed molecules due to the long and strong optical interaction of surface-bound chromophores with the evanescent field that emerges from a guiding thin-film wherein the propagating light is mostly confined. The value of the sensitivity enhancement factor, usually defined as the ratio of the absorbance measured with a waveguide platform normalized by the absorbance measured in direct transmission, can be 4-5 orders of magnitude for a single-mode integrated optical waveguide. In addition, broadband couplers for single-mode integrated optical waveguides have enabled spectroscopic capability to the technique, which then has been demonstrated to be a powerful tool for physical/chemical studies of surface-bound biomolecular materials even at the submonolayer regime. Polarized absorbance data measured with a waveguide-based platform can be directly related to the spectroscopic properties (molar absorptivity, surface concentration, order parameters) of the molecular layer under investigation. In this work, we experimentally investigated the effects of sodium chloride on the molar absorptivity and surface density of a submonolayer of chlorophyll a adsorbed onto hydrophilic and hydrophobic solid/liquid interfaces. Chlorophyll a with a constant bulk concentration (1.4 micro-molar) was dissolved in phosphate buffer

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solutions (7 mM) of neutral pH, but with different sodium chloride concentrations. For a buffer solution of 1 mM of sodium chloride, the measured surface density of chlorophyll a was 0.209 pmol/cm2 for a hydrophilic and 0.125 pmol/cm2 for a hydrophobic surface. For a phosphate buffer solution of 10 mM of sodium chloride, the measured surface density of chlorophyll a was 0.528 pmol/cm2 for a hydrophilic and 0.337 pmol/cm2 for a hydrophobic surface. Additionally, a hypsochromic shift of the Soret band was observed for the adsorbed pigment in correlation with an increase in buffer ionic strength. The adsorption of chlorophyll a onto different surfaces can play an important role to elucidate several processes found in nature and provide a rationale for bio-inspired new material technologies.

8073A-23, Session 5

Nanosensors and nanoprobes: from cell exploration to medical diagnostics

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This lecture presents an overview of recent advances in the development of optical nanosensor and nanoprobe technology at the nexus of engineering, biology, medicine and nanotechnology. This presentation describes two areas of research related to the development of nanoprobes and nanosensors for single-cell analysis and imaging: (1) plasmonics "molecular sentinel" nanoprobes using surface-enhanced Raman scattering (SERS) detection, and (2) nanosensors for in vivo analysis of a single cell for molecular diagnostics and imaging, and ultra-high throughput screening. A new generation of nanosensors and nanoprobes combining bio-recognition and nanotechnology have been developed for in vivo monitoring of biochemical processes in a single living cell. These studies demonstrate applications of plasmonics "molecular sentinel" nanoprobes for diagnostics of diseases such as HIV, and cancer; and the use of nano-biosensors for measurements of molecular signaling pathways inside a single cell. These nanodevices could also be used to develop advanced biosensing and bioimaging systems in order to study in situ intracellular signaling processes and to study gene expression and molecular processes inside individual living cells. Such nanoprobes open new horizons to a host of applications in medical diagnostics at the point of care, global health, molecular imaging, biology research, ultra-high throughput screening, and investigations of the therapeutic action of pharmaceutical agents.

8073A-24, Session 5

Raman microspectroscopy based sensor of algal lipid unsaturation

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Raman spectroscopy is a powerful analytical tool to identify sample structures. This technique can elucidate fundamental questions about the metabolic response and intercellular variability on single cell level. Thus, Raman spectroscopy can significantly contribute to the study and use of microalgae in systems biology and biofuel technology. Raman spectroscopy can be combined with optical tweezers and with microfluidic chips so that this instrument is capable to measure nutrient dynamics and metabolism in vivo, in real-time, and label free making it possible to detect population variability as a biosensor.

Algal lipids are promising potential products for biofuel as well as for nutrition. Important parameter characterizing the algal lipids is the degree of unsaturation of the constituent fatty acids. We have demonstrated the capacity of the Raman microspectroscopy to determine the degree of unsaturation in lipid storage bodies of individual living algal cells employing the characteristic peaks in the Raman scattering spectra as the markers defining the ratio of unsaturated-to-saturated bonds of the fatty acids in the algal lipids. The Raman spectra were collected from different algal species cultivated in the stationary phase for a prolonged period, inducing an overproduction of lipids.

We have shown that various algal species display significantly different unsaturation of their storage lipids, which is important finding for the biofuel production and food industry.

8073A-25, Session 5

Optical pH nanosensing with modified carbon nanotubes

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The use of nanomaterials (i.e. quantum dot, nanoparticles, organic and inorganic nanotubes, nanorods) is currently receiving a more and more growing interest in biological field because these nanodimensional structures can conveniently allow the preparation of small probes to spy at the cellular mechanisms without interferences. Among nanostructures, carbon nanotubes (CNTs) have received in the last few years an increasing attention because of their unique mechanical, thermal and electrical properties. Multi-walled carbon nanotubes (MWCNTs) functionalized with carboxylic acid (MW-COOH) were investigated as macromolecular carriers for the preparation of pH sensor dyes to be used inside cells. The activation of carboxylic groups with thionyl chloride (SOCl2) followed by reaction with a family of fluorescein ethylene glycol derivatives led to the covalent anchoring of the dyes to the CNT surface. This type of functionalization was found suitable for preserving the fluorescence properties of the dye, while providing at the same time higher water solubility to the modified macromolecular systems as compared with pristine carbon nanotubes. The use of polyether spacers between the dye and the nanotube surface was used to avoid undesirable fluorescence quenching effects. Fluorescence measurements conducted on fluorescein functionalized CNTs dispersed in water showed good pH dependence in the 5-8 pH range with excellent sensitivities. Dye-excitation was obtained by means of a laser diode with a peak emission at 488 nm. An optical fibre orthogonally placed in relation to the excitation beam and connected to a spectrum analyzer, made it possible to record the fluorescence spectra of the nanostructured material. In a typical procedure 1.2 mg of the modified MWCNT is suspended in 10 ml of deionized water and sonicated until a black stable ink solution/suspension is obtained. Samples were prepared by diluting 350 ml of the latter solution in 5 ml of water at the desired pH as to obtain a final solution of about 9 mg of MWCNT per litre. The pH of the solution was adjusted in the range 4-9 pH units by adding drops of hydrochloric acid and sodium hydroxide. Dye excitation was obtained by means of a laser diode with emission peak centred at 488 nm. An optical fibre (core diameter = 1 mm), positioned at 90° with respect of the excitation beam direction, is connected with an ANDOR optical spectrograph for the recording of the fluorescence spectra. The modified MWCNTs exhibited linear pH dependence in the range between 5.5 pH and 7.5 pH units with a sensitivity less than 0.1 pH units.

8073A-26, Session 5

A porous silicon based microfluidic array for the optical monitoring of biomolecular interactions

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The microarray technology has demonstrated a great potential in drug discovery, proteomics research, and medical diagnostics. The key issue is the very high throughput of these devices due to the large number of samples that can be simultaneously analyzed in a single parallel experiment. Further advantages are fast time analysis and small reagents consumption. The microarray technology is based on the immobilization of a large amount of highly specific recognition elements on a solid platform. Different types of platform surfaces have already been explored; the most common examples are the derivatized glass substrates and the gold/aluminum ones. In recent years, porous silicon (PSi) has emerged as interesting support for the immobilization of biological probes due to its sponge-like morphology characterized by a specific surface area of about 500 m2 cm-3. PSi is

fabricated by electrochemical etching of doped crystalline silicon in an aqueous solution of hydrofluoridric acid (HF). The PSi can be simply described as a network of air holes in a silicon matrix: its dielectric properties, and in particular the refractive index, depend on the content of voids, which can be accurately controlled by tuning the process parameters, so that different structures (Fabry Perot interferometer, Bragg mirror, optical microcavity, aperiodic multilayered sequences, optical waveguide) showing good quality optical responses can be obtained. We have already proposed a 2D-microarray for the detection of label-free DNA-DNA interactions, based on PSi photonic crystals as functional platform. In this work, we have integrated the microarray with a four-channel microfluidic system which allowed the selective functionalization of the PSi elements.

8073A-27, Session 5

Gamma-ray sensor based on microdisk whispering gallery modes

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Nuclear radiation sensors are widely used in applications such as environmental monitoring, civil protection, radiotherapy, high-energy physics, material-level measurement in adverse environments, nuclear login oil industry and cosmic rays detection. Interacting of Gamma radiation with matter, leads production of some defects. In the most cases, the effect of interaction of ionizing radiation with material establishes color centers. The creation of color centers cause optical absorption at some wavelengths and therefore can extend the absorption band. It was found that Gamma radiation increase the real part of refractive index of doped glasses, V-number, numerical aperture and number of modes.

Optical microcavities in disk, toroidal, cylindrical, steroidal, spherical and spheroidal shapes, are known to allow the buildup of large energy density at resonance state. The frequency of these so-called whispering gallery modes (WGMs), characterized by the number of wavelength within a closed circumference, are sensitive to refractive index of cavity and surrounding medium, thickness of added layer, shape deformation and separation distance of coupled fiber and cavity. Among these parameters, we found the dependency of resonance frequency of WGM is extremely sensitive to refractive index variations, allowing one to design sensor to detect Gamma radiation very well.

In this work, to the best of our knowledge, for the first time we used microcavity WGMs to investigate the feasibility of a Gamma sensor in the range of 0 to 1.2 MGy whose data are available. We coupled a 7.5 µm radius microdisk to a fiber optics. The material used for microdisk is Ge-doped silica whereas for fiber is pure silica. The reason why we chose their materials is that Ge-doped shows variation in its refractive index if exposed to Gamma radiation whereas pure silica does not. Also, the variations of Ge-doped silica refractive index is more than other doped silica such as N-doped silica. We shined the fiber with a tunable laser. If the condition of $2\pi rn=m\lambda$ is met, where r is the microdisk radius, n is its refractive index, m is an integer value and λ is laser wavelength, the resonance occurs and a very large portion of laser energy can penetrate into the disk. We saw a linear shift in resonance frequency if the refractive index changes, but the variations of refractive index versus Gamma does is not linear. The resonance frequency was found to be a subtle dependence on refractive index and any small change in refractive index leads to a shift of resonance frequency. The quality factor of microdisk defined as $Q=\nu/\Delta\nu$ was calculated as 2752 at ν=275.2THz and the free spectral range calculated as 4.482 THz. The resonance frequencies were calibrated versus Gamma intensity with a formula fitted as $f=275.2010-0.2189\gamma+0.1963\gamma^2-0.7620\gamma^3$ which shows the variations of resonance frequency versus Gamma dose. We did not expect a linear curve for resonance frequency against dose, since according to experimental data, the variations of refractive index of Ge-dopped glass against Gamma dose is not linear.

This paper is concluded with feasibility of fabrication of a Gamma dose-meter with help of microcavity allowing a high sensitivity and along with compact size.

8073A-28, Session 7

Routine optical resting heart rate sensing with a mobile phone video unit

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Resting high rate has been confirmed recently as a simple independent risk factor and marker of cardiovascular diseases. In particular, an elevated resting heart rate that develops or persists has been associated with significantly increased risk of death from heart disease or other causes. Consequently, the predictive value of resting heart rate measurement over time is more valuable than a single measurement. In this paper we detail how a mobile phone video unit can be exploited for optical heart rate sensing based on photoplethysmography principles allowing routine self-measurement and self-monitoring of resting heart rate by citizens, both patients and non patients. Our approach represents an improvement over traditional sensors for heart rate that are designed for diagnostic use in a clinical setting and are unsuited for a user untrained in their use. In addition our approach represents an inexpensive alternative to the numerous commercial devices specifically developed for the fitness market.

8073A-31, Session 7

Measurement of dynamic variations of polarized light in processed meat due to aging

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The propagation of laser light in biological tissues is of growing importance in many medical and food applications. This problem is seriously studied in live science. The accuracy of models depends upon how well the optical properties of tissues are known. Optical parameters are obtained by transforming measured optical quantities into parameters which characterize light propagation in tissue.

The biological tissues consist of cells which dimensions are bigger than wavelength of visible light and display large compositional variations, inhomogeneities, and anisotropic structures. Therefore a Mie scattering of transmitted or backscattered light occurs and different polarization states arise.

The changes of polarization state due to the multiple scattering of light in the biological cellular tissues allow measure the freshness or aging of processed victuals. The transmitted and reflected or backscattered laser light exhibits multiple scattering on the thin slice of sample. The phenomenon is different if the cellular tissues are living or dead.

The food industry is a one of most important global business. In this industry, quality is becoming an important issue consisting in an integrated measure of many parameters as purity, texture, appearance, flavor, workmanship, and color.

In the case of meat, there are temporal and dynamic changes not only as a result of chemical process, but also geometric deformations due to the water evaporation from intracellular and extracellular sites. The polarization measurement shows the changes in polarization orientation due to the muscle orientation and meat aging.

Two types of measurements were provided:

1. Measurement of polarized light reflected and twice transmitted forward and backward through the biological tissue sample - meat slice attached on sample holder mirror.

2. Measurement of polarized light transmitted through the biological tissue sample.

The relationship between polarization changes and meat freshness, and a dynamic temporal behavior of polarization states in the aged meat is reported.

8073A-36, Session 7

Optical biosensor based on His6-OPH for organophosphate detection

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There is considerable interest in the enzymatic detection and detoxification of organophosphorous compounds (OPC), derivates in orthophosphoric and alkylphosphonic acids. These include pesticides widely used in agriculture which accumulate in the ground and water sources, as well as neurotoxic chemical warfare agents. In this respect, OPH (EC 3.1.8.1) is the most important enzyme, as it catalyses the hydrolysis of very wide spectrum of neurotoxic organophosphorous compounds [1]. Recently, it was shown that a hexahistidine (His6) tag fused to OPH changed the catalytic and physical chemical properties of the enzyme, improving the catalytic efficiency, especially towards P-S-containing substrates, and the stability under alkaline hydrolysis conditions compared to native OPH [2].

In recent years, sol-gel chemistry has provided a versatile method for immobilizing and stabilizing a wide variety of enzymes and other biological molecules in transparent inorganic matrices [3]. The sol-gel process is performed under mild conditions and the properties of the final framework (diffusion within the matrix, porous structure, thickness, etc.) may be modulated by the chemical nature of the precursors, the water-to-silane molar ratio, the reaction medium and the enzyme concentration.

In this work we describe a way of immobilizing the hexahistidine-modified OPH (His6-OPH) enzyme via sol-gel technology in a porous material by retaining its catalytic activity. Potential use of each bio-sensing material was checked by the quantifying of their enzymatic properties, such as the relative activity of the immobilized enzyme, its Michaelis-Menten equasion parameters and stability under extreme working conditions (pH, T, organic solvents, etc.). Bio-sensor material was also characterised by sensor characteristics, such as dynamic range, response time, reversibility and sensitivity.

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8073A-29, Session 8

Fluorescent-based chemical sensor for organophosphate detection

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The World Health Organization has reported that each year approximately 3 million people are poised by organophosphates substances (pesticides and nerve agents) resulting in 220,000 deaths. Organophosphates are toxic compounds which causes rapid and severe inhibition of serine proteases, most markedly acetylcholinesterase, which is vital to nerve function. This inhibition is often fatal. A release of a nerve agent has the potential to rapidly affect a large number of people. The ease of manufacturing and dispensability nerve agents, as well as available, inexpensive starting materials makes these agents a weapon of choice for criminal terrorist attacks. One of the major steps toward protection against dangerous substances is to develop sensor devices that can act as an early warning system to the endangered people.

Nanotechnology represents nowadays an important process in a trend for progressive miniaturization, novel nano-sized materials and devices. The sensor characteristics can be tuned not only by the choice of the indicator and polymeric support but also by merely reducing the size (100 nm) [1]. This is because materials that are smaller than the characteristic lengths associated with the specific phenomena often display new chemistry and new physics that lead to new properties that depend on size. Perhaps one of the most intuitive effects is due to the change in the surface-to-volume ratio. When the size of the structure is decreased, this ratio increases considerably and the surface phenomena predominate over the chemistry and physics in the bulk. Therefore the sensor characteristics, such as sensitivity [2] and response time [3] can be dramatically improved.

Here, we present an optical sensor for the detection of organophosphates by incorporating fluorescent indicator dye in silica nanoparticles and sol-gel thin film. The aim of our work was to prepare stable sensor of different configurations in order to evaluate the effect of active sensor element size on the sensor performance.

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8073A-32, Session 8

Sol-gel based optical chemical sensors

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Optical chemical sensors are capable of continuously recording a chemical species and thus have found numerous applications in areas such as the chemical and food industry, in biotechnology and medicine. They have attracted great interest due to their numerous advantages over conventional electricity-based sensors and such factors as the availability of low-cost, miniaturized optoelectronic light sources and detectors, the need for multianalyte array-bases sensors, and the trends toward sensors networks. Moreover, some other properties, such as lower sensitivity to electromagnetic noise, compatibility with optical fibers, and the potential to detect multiple gases from differences in the intensity, wavelength, phase and polarization of the output light signals are also appreciated.

The growing activity in the field of optical chemical sensors has resulted in numerous sensing schemes, new indicator dyes, various polymeric matrix, size and shapes and highly diversified methods of immobilization. The sensor characteristics are dependent upon the choice of indicator, polymer, immobilization technique, and also size.

The choice of polymer is governed by the permeability of the polymer for the analyte, its stability and availability, its suitability for dye immobilization, its compatibility with other materials used in the fabrication of optical chemical sensors, and its compatibility with the sample to be investigated. Sol-gel technology provides a low-temperature method for obtaining porous silicate glass matrices. It enables to obtain material in the form of films, powders, monoliths or fibre. Organic reagents and molecular receptors can be easily immobilized in the matrices. The sol-gel matrix offers several advantages in sensor applications such as optical transparency in a broad wavelength range from UV to IR, chemical and thermal stability, and sol-gel materials do not need plasticizers for a fast sensor response. Moreover, one of the unique features of the sol-gel process is that the properties of the final network structure, such as hydrophobicity, thickness, porosity, flexibility, reactivity and stability can be easily tailored by controlling the process conditions, the type and the size of the precursors and catalysis.

Here we will report about several sensor designed over the years based on sol-gel materials for monitoring and controlling different parameters, such as heavy metals, amines, phosphates, organophosphates.

8073A-33, Session 8

Novel optical sensors for detection of nitroaromatics based on supported thin flexible poly(methylhydrosiloxane) permeable films functionalised with silole groups

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Chemical sensors for detection of traces of explosives, in particular nitroaromatic compounds, are of great current interest for purposes of public security and environmental protection. A variety of conjugated polymers have been used as sensors for nitroaromatics explosives detection4 including metallole-containing polymers. The first metallole to be used was a polysilole, and polymers and nanoparticles containing silole groups are of particular interest. Silole molecules and polymers exhibit aggregation-induced emission (AIE) caused by the restricted intramolecular rotations of the peripheral aromatic rings about the axes of the single bonds linked to the central silole cores. The emission is quenched by nitroaromatic compounds, the effect being enhanced by Lewis acid-base interactions between the silacycle and the nitroaromatic compound.

However, polymer-based sensors made from linear uncrosslinked polymers usually suffer from the drawback of polymer leakage into the medium and ensuing shortened lifetime and inefficient analyses. We report here the development of a new family of fluorescent film sensors for which these disadvantages have been overcome, made from thin films of crosslinked resin covalently bonded to the substrate and containing a very low concentration of silole groups. They exhibit the AIE effect owing to restricted intramolecular rotation, and show enhanced sensitivity to nitroaromatic analytes because of the very low concentration of silole groups. Thus, a new silole bearing an allyl group at silicon has been incorporated into previously-reported novel reactive polysiloxane coatings made from polymethylhydrosiloxane (PMHS) polymers crosslinked by the sol-gel process allowing subsequent functionalization by hydrosilylation of the SiH reactive groups. The films can be used to test for nitroaromatics present not only in the vapour phase but also in many types of solvent because of the robust nature of the crosslinked network and covalent bonding to the substrate. They can be made in thicknesses ranging from 20 nm up to 1 mm. The silole groups are readily accessible, and the sensors can be regenerated by washing with solvents such as chloroform.

8073A-34, Session 8

Sensitivity of silica microspheres modified by xerogel layers to toluene and ethanol

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Recently, spherical microresonators have intensively been investigated for chemical and biological detection [1]. In these microresonators, light of resonant frequencies circulates along the curved inner surface in the form of whispering-gallery modes (WGMs). In WGM-based sensors, refractive-index changes of the surrounding medium lead to a shift in the resonant frequency, which serves as the sensor output. The detection sensitivity of WGM sensors correlates with the quality factor Q (Q factor) of the microresonator. Q factors as high as 106 and detection limits on the order of 10-7 RIU have been achieved with optical microspheres. In biosensors, various biochemical transducers, e.g. enzymes, are bound to the microresonator´s surface. Different types of silanes or polymers have been used for the preparation of functional layers making possible to bind biochemical transducers to the microresonator surface [2]. This functional layer, however, has to be very thin, 10 to100 nm, in order to enable the interaction of WGMs with the transducer. This paper presents results on the modification of the surface of silica microspheres with a thin xerogel layer prepared by the alkoxide sol-gel method. It shows effects of this modification on the sensitivity of the microspheres to toluene and ethanol in gaseous mixtures with nitrogen and ethanol dissolved in water.

Microspheres with diameters ranging from 200 to 400 µm were prepared by heating the tip of a silica fiber with a hydrogen/oxygen burner. The microspheres were modified with a silica xerogel layer by dipping them into diluted sols of tetraethoxysilane and slowly withdrawing.

WGM resonances of the microspheres were measured in experiments where the microsphere was excited by a tunable diode laser with a linewidth less than 300 kHz. Light was coupled into the microsphere via a fiber-optic taper with a waist diameter of 3 m. The Q factors determined from the resonances were on a level of 105 - 106 .

For sensitivity tests a microsphere was fixed in a glass capillary making possible its contact with gaseous mixtures of toluene or ethanol in nitrogen. A shift of a selected WGM resonance due to this contact was measured. Effects of different solutions of ethanol in water on WGM resonances were also determined and discussed in the paper.

This work was financially supported by the Czech Science Foundation (contract No. 102/09/1763).

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8073A-37, Session 8

Photoacoustic detection of volatile organic compounds

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A considerable number of sensing applications concern the detection of volatile organic compounds (VOCs). These hydrocarbons play an important role in numerous industrial processes and particularly the concentration of hazardous and toxic species such as benzene, toluene or xylene (BTX) has to be sensitively measured and controlled.

However, detection of VOCs can as well assist medical diagnostics. A number of diseases, for instance, leave a characteristic “molecular fingerprint” in a patient’s breath. Current research in this field shows that VOCs, such as alkanes and methylalkanes, could act as biomarkers for specific cancer.

We present first results of a research project that has the goal to develop a sensor for VOCs with extraordinarily high detection sensitivity and detection selectivity. Due to its high potential concerning these two key parameters, optical spectroscopy is employed. The new detection scheme is based on photoacoustic spectroscopy (PAS). Photoacoustic detection utilizes the fact, that the excitation energy of light absorbing molecules is essentially transferred into kinetic energy of the surrounding molecules via inelastic collisions. This causes a local pressure increase in the absorbing gas. If the excitation source is modulated, a sound wave is generated that can be detected by a microphone and phase-sensitively measured using a lock-in amplifier. A considerable challenge of this project is represented by the broad and strongly overlapping absorption bands of the hydrocarbons. A discrimination of the different VOCs is possible only by using a spectrally tunable monochromatic radiation source in combination with a sophisticated data analysis algorithm. Therefore, we apply an optical parametric oscillator (OPO) with spectral emission between 3 and 4 µm together and use multivariate calibration.

The new sensor will be a platform technology that can be easily modified to fit other important applications that require the detection of complex molecules. These are for instance the sensing of biological and chemical warfare or explosives as well as the detection of doping or drugs.

8073A-38, Session 9

Infrared semiconductor laser-based trace gas sensor technologies: recent advances and applications

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This talk will focus on recent advances in the development of sensors based on infrared semiconductor lasers for the detection, quantification, and monitoring of trace gas species as well as their applications to environmental monitoring, medical diagnostics, industrial process control, and security. The development of compact trace gas sensors, in particular based on quantum cascade (QC) and interband cascade lasers, permits the targeting of strong fundamental rotational-vibrational transitions in the mid-infrared, that are one to two orders of magnitude more intense than overtone transitions in the near infrared [1].

The architecture and performance of several sensitive, selective, and real-time gas sensors based on near and mid-infrared semiconductor lasers will be described. High detection sensitivity at ppbv and sub-ppbv concentration levels requires sensitivity enhancement schemes such as multipass optical cells, cavity absorption enhancement techniques, or quartz enhanced photo-acoustic absorption spectroscopy (QEPAS) [1,2]. These three spectroscopic methods can achieve minimum detectable absorption losses in the range from 10-8 to 10-11 cm-1/√Hz.

Two recent examples of real world applications of field deployable PAS and QEPAS based gas sensors will be reported, namely the monitoring of ammonia concentrations in urban environments and exhaled human breath analysis. The monitoring of ammonia in exhaled human breath using a laser spectroscopic technique can provide fast, non-invasive diagnostics for patients with liver and kidney disorders [3]. The exhaled ammonia concentration measurements are obtained with QEPAS using a compact mid-infrared, continuous wave (cw), high performance, distributed feedback (DFB) QCL. The QEPAS technique is very suitable for real time breath measurements due to the fast gas exchange inside an ultra-compact gas cell. The minimum detectable NH3 concentration that is achieved with a thermoelectrically cooled, 20mW, cw, DFB QCL operating at 10.34 µm (965.35 cm-1) is ~ 4 ppbv (with a 1 sec time resolution).

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8073A-39, Session 9

Spectroscopy gas sensing based on hollow waveguides

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A concept of a relatively compact spectroscopy gas sensor has been developed to detect in particular weakly absorbing gases in real time. As proof-of-concept, an oxygen sensor for the A-band at 760 nm was built. The sensor comprises a laser source, a photodetector and a hollow waveguide which contains the gas under observation and guides the laser light. A tunable narrowband VCSEL laser diode was used as laser source. The waveguide is a critical part of the sensor because it should provide long absorption path but low attenuation to enhance sensitivity of the sensor in particular for weakly absorbing gases. In [1] it was claimed the possibility of detection of absorbing gases, e.g. methane, with photonic fibres. The sensor developed on this work has the capability to detect oxygen, which has absorption lines approximately 20 times weaker than methane [1].

One of the key features for the sensor is the type of waveguide. We have analysed the attenuation, spectral transmission properties and filling time of two different hollow waveguides, photonic crystal fibres and hollow metal-coated capillaries, with respect to their suitability for gas sensing. Hollow-core photonic fibres promise low attenuation at relatively long path lengths and can be bended into small diameters, which makes it possible to create/enables very small gas cells for gas sensing. However, those fibres show statistical variations of their transmission spectrum hardly reported in literature. These statistical variations limit the detection in particular of weakly absorbing gases. Their small core also limits the response time of the sensor due to the long time to fill the fibre. Hollow metal-coated capillaries do not present variations on their transmission spectrum and they have a broadband transmission which means they can be used for a wide range of wavelengths. Moreover, they can be filled very quickly, within a few seconds and thus enable real time measurements. On the other hand, they present relatively high attenuation. Their large core diameter limits the minimal bending radius of the waveguide, which in turn limits the minimal size of the sensor. Measurements and simulations have been carried out to optimise the geometry of the hollow capillary to find the best achievable sensitivity of the sensor. Measurements to characterise hollow capillaries in the infrared spectral range can be found in [2].

The intensity signal measured with the photodiode is evaluated by means of the HITRAN database [3] in order to determine the concentration of the gas under investigation without the need of a reference cell. The sensor design is applicable also for other wavelength ranges whereas only few parts of the sensor must be changed in order to adapt it for other gases.

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8073A-40, Session 9

Visual gas sensors based on dye thin films and resonant waveguide gratings

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A colorimetric sensor that provides a direct visual indication of chemical contamination has been developed. The detection is based on the color change of the reflected light after exposure to a gas or liquid. The sensor is a combination of a chemically sensitive dye layer and a subwavelength grating structure in order to enhance the color change.

The indication is clearly visible by human eyes. To enhance the perception of color change, a reference sensor sealed into a non contaminated atmosphere is used and placed just next to the sensor.

The device is based on photonic resonant effects, the visible color is a direct reflection of some incoming light no additional supplies is needed. This makes him usable as a standalone disposable sensor.

The dye thin film is deposited by Plasma enhanced chemical vapour deposition (PECVD) on top of the subwavelength structure. The later is made by a combination of replication process of a Sol-Gel material and thin film deposition.

Low cost fabrication and compatibility to dangerous environment where electricity can't be use makes this device very attractive like for applications areas in hospitals, industries, explosives, traffic...

This work was realized within the PHODYE STREP project a collaboration of the 6th framework program priority Information Society Technologies.

8073A-41, Session 9

Modulation cancellation method in laser spectroscopy

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An innovative spectroscopic technique based on balancing and cancellation of modulated signals induced by two excitation sources will be reported . The basic idea of the modulation cancellation method (MOCAM) is that the respective powers and modulation phases of the two lasers resonant with two selected absorption lines are adjusted in such a way that the signal detected from the reference sample is zero. In this case, the signal from the analyzed sample will be directly proportional to the deviation of the absorption line strength ratio from the reference ratio in the optical configuration. We use quartz enhanced photoacoustic spectroscopy (QEPAS) in a 2f wavelength modulation mode as an absorption sensing technique and employed the MOCAM approach for spectroscopic measurements of small temperature differences in a gas mixture and detection of broadband absorbers.

Spectroscopic temperature measurements are based on the temperature T dependence of absorption line strength ratio for a pair of optical transitions of the same chemical species with different lower level energies. For small ΔT, the temperature difference between two samples can be calculated using a simple equation $\Delta T = C \cdot S/S1$. Here S is the signal detected from the analyzed sample when the signal from the reference sample is zero; S1 is the signal detected from the analyzed sample when the laser resonant with the weaker line of the two optical transitions is switched off (or its modulation is disabled), and C is a constant which is determined by an initial setup calibration. A C_2H_2/N_2 gas mixture with a 0.5% C_2H_2 concentration was used as a test analyte and the detection of temperature changes with a sensitivity of 30 mK in 17s was recently demonstrated.

Spectroscopic detection of species with broad irresolvable absorption features, which is a characteristic feature of many polyatomic molecules requires optical sources with wide spectral coverage. For this application the use of semiconductor lasers is problematic since they usually cannot be wavelength modulated sufficiently to cover the entire congested absorption feature. Thus, detection of such molecules requires amplitude modulation of the laser radiation. The scattered and subsequently absorbed light creates an incoherent background making low-level concentration measurements difficult. The MOCAM method can be applied effectively to suppress this background. This requires that one of the lasers is centered on a target absorption band while the second source is tuned to the background region. When the two lasers are modulated with a 180º phase shift and the intensities are balanced properly, the acoustic signal induced by spectrally nonselective absorption of stray radiation is cancelled, and the detected signal is proportional to spectrally selective optical absorption by the targeted chemical species. This method was verified by the detection of hydrazine (N_2H_4). Two independent wide stripe Fabry Perot diode lasers were used to detect the near-infrared absorption of hydrazine vapor. Experiments showed an unwanted background suppression of ~ 100 to 1000 times compared to unbalanced (one laser) detection. The N_2H_4 vapor detection limit was estimated to be ~1 ppmV in 1s.

8073A-35, Poster Session

Lanthanide chelates sol-gel based optical sensor

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The photoluminescence properties of rare-earth (lanthanide compounds) have been fascinating researchers for decades [1]. Lanthanide complexes display large Stokes´ shifts that easily permits selective detection of the specific chelate signal and suppression of scattered excitation light; the narrow emission bands allow efficient separation of several luminescence signals in multicolour assays. Further, their very long luminescence lifetime permits gated detection (temporal filtering) on a micro- to millisecond timescale, to avoid typical short-lived (ns) non-specific background signals.

The sol-gel process is a versatile method of producing silica glasses due to the inherent advantages of the low temperature processing, and high control on the purity and homogeneity. The SiO_2 porous xerogels have various excellent properties and gradually receive significant attention for their potential applications. The purely inorganic glasses that are prepared by the controlled hydrolysis of metal alkoksides have some disadvantages (low solubility and complex crystallization, tendency of such glasses to crack) if one wants to entrap molecular lanthanide complexes in the glass matrix. The problem can be overcome by applying organically modified silicates (ormosils) in which tetraalkoksysilane precursor is partially replaced by the trialkoxysilyl compounds. Such network modifiers also reduce the maximum functionality of the silicon atoms, and therefore, they make the network less rigid and brittle.

Lanthanide-containing organic-inorganic hybrids combine the intrinsic characteristics of sol-gel derived hosts (e.g. versatile shaping, excellent optical quality, encapsulation of large amounts of isolated emitting centers protected by the host) and the luminescence features of lanthanide complexes (narrow bandwidth, long-lived emission, large Stokes shifts, ligand-dependent luminescence sensitization) [2].

As the lanthanide complexes are often not stable in the acidic precursor solution the lanthanide salt can be added to the precursor solution instead of the complex. The complex is formed in situ during transformation of the gel into a xerogel.

Only a few studies have focused on the influence on the type of organosilicon precursor on the luminescence performance of the resulting lanthanide-doped ormosils. Therefore, our study will present the successful encapsulation of lanthanide complexes (based on Eu^{3+} and Tb^{3+} ions) in the sol-gel matrix, using different sol-gel precursors (such as tetraethoxysilane, methyltrimethoxysilane, 3-glycidoxypropyltrimethoxysilane, 1,2-bis(triethoxysilyl)ethane) and their mixtures. Lanthanide complexes were incorporated into sol-gel net by two different procedures: by in situ and by the impregnation method. Finally, all prepared glass slides were characterised according to the luminescence properties of the doped lanthanide complexes, mechanical stability, leaching properties, film homogeneity, etc..

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8073A-42, Poster Session

Color stabilizes textbook visual processing

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Optical research is a means to warn against cost savings in education that could deter achieving the overall goal. We invited six 7-year old pupils, three boys and three girls, to read their ABC-book with color cover and black-and-white pages. The pages were scanned and presented on a PC screen. We used infra-red eye-tracking to monitor their performance. The eye-tracker was a remote device with a sampling rate of 250 Hz and was situated under a 22 inch LCD monitor, thus was not distractive to children. The research followed the Medical Ethics guidelines.

The average duration of eye stops for information processing, fixations, ranged from 110 to 430 msec for the black-and-white text and images. In turn, the spread was smaller for the cover that had color elements, from 160 to 330 msec. Correlation between average fixation duration and their count by reader was -.716 for the black-and-white pages and -.534 for color, Pearson's r.

We could register eye positions of first graders with an infra-red sensing device. Albeit the six readers had mastered reading at different levels, all consistently used either longer fixations, or more of them for a certain number of words. This was observed for monochrome and color pages, yet the link was weaker for the color bitmap. There a relatively smaller fixation count was possible when shorter fixations were recorded. It is tempting for a publisher to take an economic

advantage of non-color print, provided that graphics remain. We counter this as optical gaze measurements signal that different page coloring may hinder incipient reading skills to form.

8073A-43, Poster Session

Agarose coated single mode optical fiber bend for monitoring humidity

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While bend loss in a single mode fiber can be considered a disadvantage in optical communications, it is possible to utilize bend loss to allow for the development of a variety of fiber devices. In a buffer-stripped bent single mode fiber, due to the change in refractive index profile of the core and cladding, mode coupling will take place between the fundamental core mode and cladding modes, as a result resonant peaks will occur in the transmission response. This response is oscillatory with respect to the bend radius and wavelength and also varies with ambient refractive index. If the surrounding refractive index of the bent fiber is changed, it will lead to a change in the coupling conditions and will result in a shift in the resonant wavelength. To utilise such a structure as a humidity sensor, a hygroscopic material, whose refractive index changes depending on the ambient humidity, can be coated over the buffer stripped fiber bend. Agarose is an unbranched polysaccharide obtained from the cell walls of some species of red algae or seaweed. Chemically, Agarose is a polymer made up of subunits of the sugar galactose. It is soluble in hot (>350C) water. The property of thin film formation, water binding capacity and refractive index variation on water adsorption of this biopolymer can be exploited for the development of fiber optic humidity sensors.

The Agarose sensor head for monitoring humidity is fabricated by dip coating the buffer striped portion of the 1060XP fiber in a Agarose solution prepared by dissolving 1 wt.% Agarose (Sigma-Aldrich) in hot distilled water. The coated fiber is kept for one day at room temperature until it is partially dehydrated or reaches the equilibrium with the ambient humidity. To make it mechanically stable the probe is then fixed on to a semi circular rod of outer diameter 30 cm forming a bend of about 1330. The humidity response of the fabricated sensor head is studied using a customised climate chamber. The power measurements were carried out using a ratiometric scheme to avoid errors induced by fluctuations in the optical source power.

Compared to the narrow operating range (80-95 %RH) of the coating Polyethylene Oxide utilised previously, the advantage of an agarose coating is that the response of an Agarose coated single mode fiber bend is linear over a much wider range of humidity variation (30 - 95 %RH). The response of Agarose coated sensor head is reversible and repeatable in nature. The fiber optic humidity sensor introduced here offers the advantages of a simple structure and low cost. These advantages would allow for the development of a disposable fiber optic humidity sensor with potential for industrial, chemical or biological applications.

8073A-44, Poster Session

Preparation and characterization of sensing layers for pH detection in living plant cells

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Local chemical sensing in living cells by fluorescence methods with submicron spatial resolution is in the scope of biologist because of bringing new information about biochemical processes in living matter [1]. One of the most important monitored variables is pH. In this contribution, several fluorescence opto-chemical pH transducers were immobilized in different matrixes and tested with respect to applied them as detection layers in fluorescence pH sensors inside living plant cells.

Selected pH opto-chemical transducers, namely ion-paired 8-Hydroxypyrene-1,3,6-trisulfonic acid trisodium salt with octyltrimethylammonium bromide (c-HPTS) [2], Oregon Green® 514 carboxylic acid (OG) and 2',7'-bis-(2-carboxyethyl)-5-(and-6)-carboxyfluorescein (BCECF) were investigated. The transducers were added separately or together with a ruthenium reference dye [3] in sols based on polymethylmethacrylate (PMMA) or on a mixture of 3-glycidoxypropyltrimethoxysilane with tetraethoysilane. The sols were dip-coated on Pyrex® glass slides forming thin layers with a thickness of about 1 m. The layers were thermally cured at 100ºC.

The prepared layers were characterized by profilometry, UV-VIS and FT-IR absorption spectroscopy. The layers were also attached into a flow-through cell of a Fluorolog 3 fluorometer where were brought into the contact with Britton-Robinson buffers with different pH values and their fluorescence was measured. The measured fluorescence changes resulting from pH changes were evaluated by two approaches. In the first approach, the ratiometric method was employed in which the sensor response was taken as a ratio of the transducer emissions excited at two different excitation wavelengths. In the second approach, the sensor response was evaluated as a ratio of the emission of the pH transducer and the emission of the reference ruthenium dye excited at the same excitation wavelength.

Inflection points on calibration curves were shifted to lower pH values from 7.5 for c- HPTS to 4.5 for OG according to the dissociation constant of the immobilized transducers. A lower limit of pH detection was 6, 5.5 and 4.5 for c-HPTS, BCECF and OG, respectively. The transducers immobilized into the PMMA matrix exhibited a longer time response to pH changes compared to the siloxane-based matrixes, however the PMMA layers showed better mechanical properties and durability in long period time testing.

Since it has been found on cellular exudates [3] that the expected pH values in living plant cells are ranging from 5 to 6.5 the results of this paper allow us to draw conclusion that OG and BCECF cover well this pH range and they are suitable transducers for pH sensors of living plant cells.

Acknowledgement

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8073A-45, Poster Session

Simulation of the response of the optical sensor based on the local plasmons in the layer of nanoparticles

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On the base of self-consisted approach with the use of Green functions we developed the model of the optical response of the layer of nanoparticles randomly distributed on the surface [1]. In contrary to the standard models of the effective medium approximation the direct electromagnetic interaction between the particles was taken into account in this model by the Lipman-Shwinger [2] equation. Previous modeling [1] demonstrated strong dependences of the optical properties of such a layer on the shape of constituting particles.

The shift of the local particle resonance by covering of particles by additional layer is well-known to be the basis of optical sensors on local palsmons. Using the developed formalism we calculated effective dielectric function of the layer of gold nanoparticles on the glass depending on the particles shape and the parameters of covering layers. Transmission spectra of such a structure show the expected shift of the plasmon resonance at the adsorption of the additional layer on nanoparticles. On the base of this model, which takes into account the interaction between particles, we can calculate the sensitivity of such a sensor and find optimal parameters of the nanoparticles to increase it.

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8073A-46, Poster Session

3 5 photodiode temperature sensors for low-temperature pyrometers

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The report considers the capabilities of low-temperature color (two-color) pyrometers with temperature sensors based on A3B5 immersion lens photodiodes in the spectral range 2-5 mcm.

The main problems caused by low-temperature pyrometry are the low level of thermal radiation of the object when it temperature is below 300 °C and a shift of the radiation maximum to the infrared spectral region. The problem of detection of weak thermal radiation in industrial pyrometers is solved by using broadband (8-14 microns) radiation detectors and temperature measurements on large object areas. Usually, such pyrometers require initial calibration at the blackbody radiation, therefore the unknown emissivity of a real object can lead to methodical measurement error up to 25-30% or more. Methods of two-color pyrometry can resolve this methodological error but they can not be realized with broadband detectors and at the present time is suitable only for temperatures higher than 500 °C. Requirements for professional pyrometer: small size of the surface being measured, high speed, accuracy and repeatability of temperature measurements- are much higher than thous for industrially produced low-temperature pyrometers.

Mid-infrared immersion lens photodiodes developed at the Ioffe Institute have high spectral selectivity ($d\lambda/\lambda max \approx 0.1...0.15$); and as to the response time (up to 1E-9 s) and detectivity ($D^* \approx$1E-9...1E-11, cm√Hz/W) they are significantly higher than for currently known detectors of thermal radiation. To estimate the prospects of their application in low-temperature pyrometers we used an approach based on an analytic description of optical sensors using the transfer function with taking into account spectral and geometric characteristics of the pyrometer optical channel, radiation characteristics of real objects, the transmission of an intermediate medium, parameters of the detection and transmission of the electronic highway and the size of the surface under the analysis.

The relatively high spectral selectivity of photodiode temperature sensors allows the use of a fundamental Planck's radiation law to calculate the radiation power of the object at the $\lambda = \lambda max$ of the chosen photodiode.

The numeric differentiation of the transfer function with taking into account the noise of the photodiode with preamplifier circuits allowed us to evaluate the potential value of the pyrometer sensitivity and sensor instrumental errors within the entire range of measured temperatures at different wavelengths λmax - 2.9, 3.3, 4.2 and 4.7 microns. Calculations showed that all the photodiodes provide high precision measurements: the absolute error of 0.01...1 °C at the temperature range 0-300 °C with the response time up to 10 mS.

The analysis of the transfer function of the temperature sensors based on A3B5 photodiodes also showed that they permit implementing the methods of the multicolor pyrometry, providing a significant decrease of the methodological error in the optical temperature measurements associated with unknown values of the object surface emissivity and uncontrollable changes in the environment transmission.

8073A-47, Poster Session

A speckle-photometry method of measurement of thermal diffusion coefficient of porous anodic alumina structures intended for optical sensing

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A highly ordered structure and a relatively simple method of obtaining porous anodic alumina (PAA) have been attracting the attention of researchers to the potentialities of using such material in various fields of science and technology. The PAA- technology is oriented to mass production, does not require the use of expensive modern lithography and evaporation equipment. The technology makes it possible to produce PAA layers in a wide thickness range (0.1 - 800 µm) and with a spatially ordered system of pores whose diameter and periodicity can be changed within the range from tens to hundreds of nanometers. By filling nanopores with conductive, semiconductive and dielectric materials or their combinations, possibilities arise of making micro-sensors based on various physical, chemical and biological effects. For numerous applications, there is a promising development direction associated with modification of PAA structures with nano-diamonds. To control the modification process and for subsequent use of films in energy-absorbing sensor systems, a real-time measurement is required of their thermal and physical parameters, and, in particular, the coefficient of thermal diffusion (CTD).

In this report an optical method for determining CTD is developed which is based on an analysis of the spatial-temporal dynamics of the speckle field. The proposed method for measuring the coefficient of thermal diffusion is based on the measurement of an average speed of the speckle-field movement along the specimen surface. Due to statistical nature of speckles, their movement must be also described statistically. Our approach consists in the use of correlation functions describing the degree of change in a speckle-image of some element of the surface in the process of heating or cooling. The proposed method is fully optical, fast, non-invasive and can be customized for specific applications. Optical measurement of CTD has been carried out for PAA structures both modified and not modified with nano-diamonds. High resolution allows one to measure spatial inhomogeneities of thermophysical properties of PAA- films.

8073A-48, Poster Session

Dependence of detected intensity of fluorescence of dye on optical fiber tapered tip diameter

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Measurements of pH in small objects (cells, liquid drops) by means of optical fluorescence-based sensors based on optical fiber tapers have been investigated, recently. [1]. Tapered fibers provided with a thin detection layer on the tip, that is sensitive to pH have been investigated in intracellular sensors [1] however, the excited fluorescence was detected by an external fluorescence microscope. The employment of a taper both for the excitation of a pH transducer and collection of the excited fluorescence from small drops of plant exudates has also been described [2]. One can expect that the diameter of the taper tip diameter determines the detected fluorescence intensity and is one of limited parameters for using of optical fiber tapers for intracellular measurements without any external fluorescence detection. This work presents results of measurements of the fluorescence intensity emitted by a dye sensitive to pH and applied onto the tip of a fiber taper by means of the taper. The dye fluorescence was excited by a blue laser, collected by the taper and detected by a spectral analyzer. Five samples of optical fiber tapers with different tip diameters were prepared on a laboratory tapering machine [3] using the same graded-index multimode optical fiber. Experimental conditions, i.e. excitation wavelength of 470 nm and output intensity of the laser, were the same for each tested taper. The obtained experimental dependence of the

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fluorescence intensity on the diameter of the taper tip allowed us to estimate a minimum tip diameter making possible reliable fluorescence measurements. The results obtained are compared with previous ones measured with different types of optical fibers (different refractive-index profiles and core diameters).

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8073A-49, Poster Session

High-sensitivity temperature sensor for spot pyrometer with in-situ calibration against real object temperature

G. Y. Sotnikova, S. E. Alrksandrov, G. A. Gavrilov, A. A. Kapralov, V. L. Suchanov, Ioffe Physical-Technical Institute (Russian Federation)

The given work it is presents a spot pyrometer on the basis of a high-sensitivity Si-photodiode sensor. The basic advantage of proposed pyrometer is in-situ calibration mode feasible against the characteristic temperature points, inherent in an object and received in situ from indirect measurements. The suggested approach does not require initial calibration of the device against the Black Body temperature and allows the object temperature sensing from 400 °C on small spots of remote objects (3-5 mm over a distance about 50 cm) under conditions of unknown emissivity ε (λ) of real object and uncontrollable intermediate environment transmittance variance. The basic attention was pay to the choice of a sensor when developing the device since its parameters define the temperature full-scale range, the value of a tool error, the response time and sensitivity of a pyrometer. In the developed pyrometer the high-sensitivity low-noise photodetector FI-1 created in Ioffe Institute is used. The photodetector represents the chip assembly of the Si p-i-n photodiode with the electronic signal processing scheme using time-pulse modulation.

In order to provide the calibration mode against the limited number of points (one point is most desirable) it is necessary to have the analytical expression connecting the object temperature under measure and registered energy of its radiation. Only monochromatic pyrometric technique allow us to use the analytical expression of the Planck radiation law (the Wien law approximation for λ <3000 mcm*) for temperature calculations. The sensor spectral selectivity is achieved by using of a narrow-band filter with λ max =0.95 mcm and dλ = 0.05mcm. The choice of a registered spectral line λ max =0.95 mcm has been caused by the problem of the real temperature control on a growing film surface on different substrates (including GaAs, transparent for λ> 1mcm) during molecular-beam epitaxy (MBE) process.

Small noise (3E-15 A) and high spectral sensitivity of the photodetector near 0.95 mcm (0.55 A/W) allow one to provide temperature sensing on small spots of an object at high speed : 2-1000 measurements per second for temperatures from 400 °C to 1500 °C respectively.

The calibration process consists in determination of a photodiode current Ic corresponding to some known temperature of calibration Tc. Taking into account this calibration mode, the equation for the connection of the running value of a photodiode current I with the actual object temperature Tx will look as:

Tx = A/{(A/Tc)-ln[(Ix-Id)/(Ic-Id)]},

where is a constant depending on the registered wavelength λ max;

Tc is the calibration temperature, K;

Ix is the running value of a photodiode current;

Ic is the value of a photodiode current corresponding to the temperature of calibration Tc;

Id is the value of the photodiode "dark" current.

The in-situ calibration tool using nominal characteristic temperature points has been realized in the pyrometer designed for the temperature control of a substrate surface during MBE growth of semiconductor heterostructures. Device calibration was performed directly during an operating cycle against the temperature lying within a range of measurements that is defined by physical points: the temperature of oxide evaporation for GaAs substrates (585(+10)°C), accompanied by fast electron diffraction on reflection (detected visually from a change in the RHEED pattern), or the temperature of the beginning of Ga evaporation from a surface of a sapphire substrate (700(+10)°C).

8073A-50, Poster Session

Photoluminescence of CdHgTe single quantum well structure as a method of IR-photodetector device design

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At present nanoheterostuctures based on semiconductor solid solution CdxHg1-xTe (MCT) and mainly structures with quantum wells and superlattices are considered as a basic material for the development of photodetector devices of a new generation for infrared range of spectrum. Thus the actual purpose for scientific and technical research is experimental study of optical characteristics of such structures and theoretical analysis of experimental data. These researches will allow understanding physical processes and possibilities of a management of MCT-based nanostructures spectral characteristics. Photodetector devices based on MCT QW will be developed on the basis of obtained data.

We have considered photoluminescence spectrum of MCT-heterostructure included single QW with well width 12.5 nm and composition into the well x = 0.24. Spectrum of photoluminescence demonstrates two accented lines of radiation with wavelengths λ1 = 3.8 µm for short-wave line and λ2 = 5.5 µm for long-wave line. Feature of this luminescence spectrum is related with the fact that the value of short-wave line intensity is greater than the intensity of long-wave line approximately four times as much. To explain this feature theoretical analysis of experimentally obtained spectrum was carried out in this work.

Energy-band diagram for the studied semiconductor structure with single QW Cd0.8Hg0.2Te / Cd0.24Hg0.76Te (d = 12.5 nm) / Cd0.79Hg0.1Te was calculated under the temperature 84 . Potential profile was computed by the numerical solving of Poisson equation with taking into account the dependence of electron affinity on the composition x of MCT. This dependence was found by us earlier. Estimation of dimensional quantization levels into the QW was found by the Schrödinger equation solution in the network of effective mass approximation.

Calculation gives next energies of dimensional quantization levels with level numbers 1 and 2 for electrons: Ec1 = 0.028 eV, Ec2 = 0.1850 eV; for light holes: Ehl1 = 0.017 eV, Ehl2 = 0.151 eV; for heavy holes: Ehh1 = 0.0037 eV, Ehh1 = 0.015 eV. It may be concluded that the next types of interband radiative transitions are allowed in the considered structure: c2-c1, c1-hl1, c2-hl2, 1-hh1, c2-hh2. Also values of overlap integrals and velocities of radiative and nonradiative Auger-recomination mechanisms for various types of interband transitions were estimated.

According to theoretically obtained data it can be concluded that wavelength related with short-wave line of luminescence (~3.8 µm) is the most suitable for the transition c2-hh2 (3.5 µm). This fact allows us to define this type of transitions is responsible for short-wave line in the spectrum. The long-wave peak of photoluminescence is observed on the wavelength ~5.6 µm and corresponds to the transition c1-hl1 with λ = 6.1 µm.

Thus to explain the distribution of luminous intensity between observed peaks we have compared ratio of velocities of radiative and nonradiative Auger-recombination for transitions c1-hl1 and c2-hh2. Values of this parameter for considered transitions is equal 3,58 and 988,65 consequently. Hence Auger-recombination in QW have a great influence on the luminescence of a structure.

Such types of transitions in a QW can be used for detection of infrared radiation and improve characteristics of photodetector devices.

8073A-51, Poster Session

Optical fiber element of whole-cell sensors of environmental pollution

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Bioluminescent bioreporters were originally constructed as whole-cells bacterial biosensors [1] that responded to specific chemicals or physical agents via production of visible light ($\lambda \approx 500$ nm). The whole-cell optical fiber sensor for real in-situ on-line monitoring of the environmental pollution in remote localities consist of bioluminescent bioreporters immobilized on the optical fiber element [2] (OFE) and sensitive photomultiplier. This sensor needs an optimal design of OFE to ensure effective coupling of low intense light produced by bioluminescent bioreporters.

We compared theoretical calculations [3] of coupling efficiency with experiments for various OFEs with immobilized bacterial bioreporters Pseudomonas fluorescens HK44 and Pseudomonas putida TVA8. Pseudomonas fluorescens HK44 is common soil bacterium with incorporated lux gene in biodegradation pathway of salicylate. This bacterium produces bioluminescence in presence of naphthalene and salicylate [4]. Pseudomonas putida TVA8 is genetically engineered bacterium producing bioluminescence in presence of BTEX. We evaluated the influence of the physical properties and geometry of the OFE, active layer and cell immobilization techniques on intensity of detected light.

The OFE performing the highest signal has been chosen for detection of bioavailability of organic pollutants in real samples of ground water contaminated with naphthalene and phenols. The samples were taken from localities in the Czech Republic. The sensor responses were compared with contents of contaminants determined by GLC standard analytical procedures.

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8073A-52, Poster Session

Fiber bragg array as a quasi-distributed temperature sensor

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This paper deals with a cascade of filter bragg gratings which serves as an quasi-distributed temperature sensor. The cascade of fiber bragg gratings with very narrow transmission band and different central wavelength. It enables to measure temperature through the drift of central wavelength of the light reflected from each grating. Using different central wavelength in each grating enables to locate in which point of the measurement set-up the temperature ganges. The whole set-up is illuminated by the tungsten halogen source Ocean Optics LS-1. Transmission characteristic of the whole systém is observed at the output face of the array.

8073A-54, Poster Session

Optical blurring sensor

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We propose to measure the blurring by using optical blurring sensor. It depends on Michelson Interferometer with He-Ne laser, which has 633nm of the wavelength and 2mW of power. The polluted water has a certain blurring. If we can measure the blurring of the water, we can say whether this water is durty or not. The sensor system shows good results to determine the % pollution of the water.

8073A-55, Poster Session

Estimation and optimization of scintillation light collection efficiency using a silicon spotomultiplier

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The detection of γ-ray by scintillation process is a common method. Collection of the light emitted from the scintillation material requires the use of a light sensor. The light sensor is essential for the conversion and amplification of the minute light output of a scintillation pulse into a corresponding substantial electrical signal.

The efficiency of light collection is mainly dependent on the optical characteristics of the radiation sensor assembly that includes the scintillation crystal, optical reflectors covering the crystal, and the medium between the crystal and the light sensor. The efficiency is also much influenced by the coupling technique and by compatibility of the specified components to each other. Finally, the collected light is converted into an electrical signal by the light sensor. The characteristics of this light sensor are critical to evaluation of the light collection efficiency.

Out of the various existing light sensors, the Silicon Photomultiplier (SiPM) is a novel and rapidly developing technology that is readily investigated in the radiation detection field. The SiPM is a multipixel semiconductor photodiode, where the pixels are jointed together on common silicon substrate. The SiPM pixel operates in a Geiger mode, with a low breakdown voltage, so the generated carrier gives rise to a Geiger-type discharge.

This work presents measurements of light collection efficiency using a detector configuration that consists of SiPM light sensor and a scintillation crystal. The detector configuration was evaluated and further optimized.

Improving the optical coupling of the light sensor to scintillation material has a major role in development of sensitive radiation detectors. The optimization improves the noise floor level and the resolution which are main parameters of the detector. These factors are critical for isotope identification capability of a radiation sensor.

The optimization process steps included matching between the scintillator's emission spectrum and the SiPM's efficiency curve, optimizing scintillator reflector design, minimizing the coupling distance and choosing medium between the scintillator and the SiPM.

The goals of characterization, definition and optimization of the operational and assembling techniques were achieved in this research. The research established a ranked outline of the most influencing parameters of the SiPM. Optimized values for the dominant parameters, such as noise level, resolution and dynamic range, were established.

8073A-56, Poster Session

An analysis method for evaluating gradient-index fibers based on the Monte Carlo method

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Gradient index (GRIN) optical fibers have excellent optical design characteristics and are widely used in optical information processing and communication applications as new optical devices. In the GRIN optical fiber the refractive index is distributed two-dimensionally, gradually decreasing from the central axis to the circumference. Since this fiber is capable of forming inverted real images or erect magnified images, it requires only a short working distance, which makes it suitable for miniature, high-performance devices.

There are two processes to manufacture GRIN optical fibers, one is the ion exchange method using inorganic glass and the other is the interdiffusion method using polymer gel, to manufacture GRIN optical fibers. Although the glass method is a batch process, the precision of forming the refractive index distribution in each batch is high and the products are also used as lenses for color applications. On the other hand, the plastic method is a continuous method with little deviation among product lots and excellent energy efficiency and environmental characteristics. However, it requires high-precision concentricity and high-precision film thickness control, and thus a large investment in facilities.

Whether a GRIN optical fiber satisfies the specified performance is usually evaluated by measuring the modulation transfer function (MTF). The most popular method for doing this experimentally is to use a square wave chart: incident light is applied to the GRIN optical fiber through the square wave chart, and the MTF is calculated based on the maximum and minimum values of the output intensity distribution. Meanwhile, the MTF of GRIN optical fibers is often evaluated using computers, with commercial optical design software programs. In this method, an incident point light source is applied to the fiber instead of the square wave chart to calculate the MTF based on the spot diagram. However, these programs use a different MTF calculation method from the theoretically true evaluation method and so their results may differ greatly from experimental results, as will be shown later. A computer-based method for accurately evaluating the performance of GRIN optical fibers is needed.

We propose a GRIN optical fiber evaluation method using a square wave chart based on the Monte Carlo method. The incident light applied through a diffuser panel is filtered through a square wave chart into a GRIN optical fiber. The incident image is reconstructed by integrating the light ray through the GRIN optical fiber on the imaging plane to evaluate the MTF. We show that the method precisely reproduces the experimental results.

8073A-57, Poster Session

A new space instrumental concept for the measurement of CO_2 concentration in the atmosphere

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Measuring the concentration of greenhouse gases from space is a current challenge. This measurement is achieved via a precise analysis of the signature of chemical gaseous species (CO_2, CH_4, CO, etc.) in the spectrum of the Earth's atmosphere. Two families of spectrometers are commonly used. The first family is based on the phenomena of interference between two radiation waves. The Infrared Atmospheric Sounding Interferometer (IASI), onboard the METOP satellite, is a good example of a fully-operational instrument of this kind. The second family is based on the use of dispersive optical components. These instruments must have high radiometric and spectral resolutions, in narrow spectral bands, in order to discriminate absorption lines from various atmospheric chemical species and to quantify their concentration. It is the case, for example, of the instrument onboard the OCO satellite.

Our analysis led us to define a new instrumental concept, based on a dispersive grating spectrometer, with the same quality level of performances but more compact and therefore less expensive.

After a description of such a spatial instrument, which uses a specific grating component, a preliminary assessment of performances will be presented, including the theoretical calculations and formula. A breadboard implementation of this specific grating allowed us to show the practicality of this concept and its capabilities. This preliminary design is encouraging and shows that such a spectrometer may be compatible with a micro-satellite platform. Some prospects of improvements are also considered.

8073A-58, Poster Session

Monte Carlo simulation of light propagation in a U-shaped optical fiber

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Monte Carlo simulation approach is proposed and applied to simulate transmission and emission characteristics a U-shaped dielectric waveguide with the cylindrical core symmetry. The physical model used comprises a coherent monochromatic photon bundle propagating within the waveguide structure under the ray approximation and self-interference conditions. The calculated light outputs are discussed in dependence on the geometry of the curved region and the propagating photon energy.

8073A-59, Poster Session

Dendrimer-based optical sensors

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The use of different materials such as magnetic nanoparticles, SiO_2 nanoparticles, quantum dots, dendrimers, polymeric nanoparticles, for the preparation of optical chemical sensors opens the door to new applications of these sensors, especially in medicine, biotechnology. Each individual material is specific and significantly affect the sensor characteristics such as dynamic range, response time, reversibility and sensitivity.

Dendrimers are well-defined highly branched regular three-dimensional macromolecules, which are characterized by the presence of a large number of functional groups on the surface and the presence of internal cavities. This unique architecture provides dendrimers with the capability to encapsulate small guest molecules into their interiors and conjugate functional molecules on the surface. Also the chemistry of the core and the surface can be tailored according to specific applications, such as catalysis, separation and sensing,... The polymeric shell of a dendrimer not only renders an indicator solubility, but also provides protection against interfering substances and has pronounced effect on diffusion of analyte molecules [1-3].

In our laboratory, we prepared fluorescent active dendrimer as a new sensing material for pH detection. For the core of the dendrimer we used magnetic nanoparticle on which optical active dendrons are convergently attached. The combination of this two exceptional materials has a significant impact on the sensor activity. The magnetic core enables moving and monitoring the sensor at a distance under the influence of an external magnetic field. Sensor material were characterised using infrared spectroscopy (FTIR), transmission electron microscopy (TEM), vibrating sample magnetometry (VSM). Sensor characteristics, such as dynamic range, response time, reversibility and sensitivity, were determinated by fluorescence intensity.

8073A-60, Poster Session

Nanosensor based on nanoparticles for glucose detection

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Worldwide, diabetes is a rapidly growing problem that is managed at the individual level by monitoring and controlling blood glucose levels to minimize the negative effects of the disease. Because of limitations in diagnostic methods, significant research efforts are focused on developing improved methods to measure glucose [1].

In this study, systematic approach towards the fabrication of highly functionalized iron-oxide magnetic nanoparticles, presently used for glucose monitoring, is herein fully presented. Magnetic iron-oxide nanoparticles were prepared using classical coprecipitation method in alkaline solution. Prior to surface modification, obtained magnetic nanoparticles were colloidally stabilized to prevent their aggregation and dispersed in aqueous solution. Primary surface modification of the colloidally dispersed magnetic nanoparticles was successfully performed by the proper deposition of thin silica layer onto nanoparticle surface under strictly regulated reaction conditions. Further, the secondary surface functionalization of the prepared nanoparticles was achieved by additional coating the particle surface with an appropriate functional ligand, bearing the functional substituents, such as amino-, carboxyl- or hydroxy- groups, in order to enhance covalent binding of fluorescent dyes of various structural types for a specific glucose monitoring (such es: HPTS, HPTS(Lys)3, PTCA, MPTS, TSPP, TCPP,...) [2].

The different phases developed during the synthesis were identified by X-ray powder diffractometry (XRD) (D4 Endeavor, Bruker AXS). For the morphology investigations the nanoparticles were deposited on a copper-grid-supported transparent carbon foil and examined by a conventional transmission electron microscopy TEM/HRTEM (Jeol JEM 2010-Fx) operated at 200 kV. The specific magnetization σs of the prepared powders was measured using a vibrating sample magnetometer (VSM, Lakeshore). The fluorescence measurements for each dye were done in-situ taking the fluorescence emission spectra [3].

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8073A-61, Poster Session

U-optrode-based fiber optic thermometers

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Extremely bent optical fiber (U-optrode) is applicable as a sensing head, signal of which is govern by refractive index and light scattering properties of the surrounding medium. The presented contribution aims to shows that when covered with properly selected polymeric transducers, the reliable and fast thermometers covering different temperature ranges can be constructed suitable for, e.g., measurements in environments with high level of electric or magnetic disturbances. Obviously, the bare optrodes can be also used as sensitive analytic tools for collecting information about thermally-induced changes of optical and micro-structural properties of polymers. Both types of application are demonstrated on the obtained experimental results.

8073A-62, Poster Session

Optimization of an integrated wavelength monitor device

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Various techniques for wavelength measurement have been recently proposed for deployment in Dense Wavelength Division Multiplexing (DWDM) for optical communication systems and for interrogation of optical sensing systems based on a wavelength-shift mechanism, such as fiber Bragg grating (FBG) sensing systems. Integrated wavelength monitors based on planar lightwave circuits have a range of advantages, such as low fabrication cost, compact size, high scalability, fast response, and also physical robustness in comparison with wavelength measurement systems based on bulk components. To date, the integrated wavelength monitors reported in the literature include directional couplers, multimode interference (MMI) couplers, arrayed waveguide gratings and a Y-branch with an S-bend arm.

A MMI coupler has a simple structure and it is conventionally used as a beam splitter/combiner. An integrated wavelength monitor based on the MMI structure exploits the wavelength dependence of interference occurring within the multimode waveguide section. Although the well-known self-imaging theory is useful in designing the MMI structure as a splitter/combiner, it cannot be used to design an MMI structure to act as an edge filter for wavelength measurements. We previously reported a design procedure where a suitable length for the multimode waveguide section can be found through scanning the multimode waveguide length for optimal MMI parameters at a given waveguide width.

In this paper, we present an alternative design method for an MMI structure based wavelength monitor, the design method includes: 1) Generation of a new set of parameters; 2) Acceptance of the new parameter; 3) Cooling schedule and termination. As shown in Fig. 1, the integrated wavelength monitor is a Y-branch with one arm serving as a reference and the other am containing an MMI structure acting as an edge filter. The corresponding physical parameters are as follows: the waveguide cross-section is 5 m 5 m. The considered wavelength range is from 1500 nm to 1600 nm and the desired spectral response of the edge filter is from 5 to 20 dB. The search range for the width of the MMI section is from 20 to 50 m. In the optimization of the MMI structure, both the length and width of the multimode waveguide section and positions of the input and output waveguides are considered, and a global optimization algorithm associated with a simulated annealing algorithm is employed. Based on the simulated annealing optimization algorithm, the final calculated results for the multimode waveguide section are W=46 m, L=4402 m, x1=20.4 m, and x2=40.7 m. A specific spectral response has been achieved with the MMI based edge filter: 1) the baseline loss is 7.17 dB@1500 nm and 2) the discrimination range is 14.13 dB which is the power difference between 1600 nm and 1500 nm. These values for baseline loss and discrimination range are typical of those found in real systems and are competitive with other approaches to edge filter implementation. The fabrication tolerance of the designed structure is also analysed in this paper.

To illustrate the light propagation within the whole device, corresponding simulated light propagation results at wavelengths of 1500 and 1600 nm utilizing the beam propagation method are presented in Fig.2a and Fig.2b respectively, displaying graphically the different transmission responses of the output arm with the MMI section at the two wavelengths. The designed MMI filter in Fig. 2a (wavelength 1500 nm) corresponds to a transmission loss of 7.17 dB and in Fig. 2b (wavelength 1600 nm), the corresponding transmission loss is 21.3 dB.

8073A-63, Poster Session

Microstructure optical fibres for detection of gaseous analytes

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In last years, optical fibres have been used not only in telecommunications but also in medicine and industry. Microstructure optical fibres are special optical fibres with air holes in the optical cladding extending along the entire fibre length. They have been employed for the development of fibre components or physical and chemical sensors [1-4].

This paper deals with microstructure optical fibres with a steering-wheel like structure which have been designed and prepared for the purpose of opto-chemical detection. The inner structure of a steering-wheel microstructure optical fibre (SW-MOF) is based on a small fibre core that is surrounded by three big air holes with triangular symmetry. The air holes in the cladding are large enough for gaseous or liquid analytes flow through the all volume of the holes [4]. Moreover, this structure guides light inside the fibre core and due to a small core diameter the evanescent wave of the guided mode penetrates into the holes and can be employed for the detection. We have tested this fibre as a tool for detection of toluene vapors.

The inner structure of the SW-MOF was prepared on the basis of numerical simulations with a core diameter of 2 um, diameter of the cladding holes of 42 um and thickness of the silica bridges between that holes of 0.9 um.

A set-up for sensitivity measurements consisted of a commercially available wideband optical source with a wavelength of 1570 nm and an optical spectrometer that detected optical power at the end of the SW-MOF. Toluene concentrations in air mixtures were set by using mass flow controllers. The mixtures with changing flow rate were injected into the SW-MOF holes via a special input chamber. In experiments transmission spectra of the fiber were measured for different toluene concentrations.

Experimental results show that the designed and prepared SW-MOF can be used for detection of toluene vapors in concentrations below tenth of molar percent in the air.

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8073A-64, Poster Session

Dark current study for CMOS fully integrated-PIN-photodiodes

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PIN photodiodes are semiconductor devices widely used in a huge range of applications, such as photoconductors, charge-coupled devices, and pulse oximeters. The possibility to combine and to integrate the fabrication of the sensor with its signal conditioning circuitry in a CMOS process flow opens the window to device miniaturization lowering the production and assembly costs. This paper presents the design and characterization of silicon based PIN photodiodes integrated in a standard CMOS process.

Specially, the work is focused on the study of the dark current behavior of vertical PIN photodiodes integrated with a CMOS standard process by means of through silicon via. The nature of the substrate, low impurity and low doped Si, together with the isolation guard ring design introduces a parasitic effect in the dark current; The dark current, then, has to be reformulated taking into account this new parasitic term. An analytical model has been already reported by us where the influence of the guard ring is modeled as a parasitic transistor.

In this work a deeper analysis of the parasitic dark current is done, based on different starting material substrates and based on different photodiode geometries. The measurements and analysis of the dark current are carried out in a wide range of temperatures in order to distinguish the different contributions to the dark current. As expected, it has been found that the generation term of the dark current is the dominant term at lower temperatures and that is mainly determined by the minority carrier lifetime of the substrate, whereas for temperatures above room temperature the diffusion current together with the parasitic guard ring component dominate. The photodiode guard ring geometry and substrate parameters determine the main contribution at high operating temperatures.

The model is used to properly design the guard ring structures taking into account the maximum dark current allowed at the operating temperature. Substrate parameters as lifetime and resistivity are extracted from the model versus the experimental data fit. In addition to that, optical measurements such as responsivity per wavelength, versus temperature and time response are described in order to correlate the optical and electrical properties of the different substrates.

Another important effect related to the dark current, which has also been investigated in this work, is the dark current dependency on the thermal cycling history. As previously reported by other authors, some alloy process steps could have a positive impact on the dark current performance. In this case, several alloys have been performed at different temperatures and at different conditions, and the impact on the dark current on different substrates will be also presented. Experimental data is correlated to surface recombination by means of device simulations.

8073A-65, Poster Session

The modulation transfer function of interframe CCD sensors

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Among the charge-coupled device (CCD) based optical sensors the interframe (IF) type arrays, due to simplicity of the photo-generated charge transferring (no mechanical or electronic shutter is required), and high frame rate, deserve special emphasis. The main drawback of IF sensors is the asymmetric nature of the fill factor in the horizontal and vertical directions: since in these sensors the area shielded from light (used for the charge transfers) is located vertically between columns the ratio of the pixel size and pixel pitch is different in the two directions. While the geometrical modulation transfer function (MTF) of an optical imaging sensor depends only on the pixel size and pitch, it is expected that the one-dimensional MTFs of an IF array sensor in orthogonal directions will be different. To the best of our knowledge, there are very few works in the literature dealing with the MTF of sparse arrays.

In this work, first, we discuss the generalized equation for the geometrical MTF of IF CCD sensors. Secondly, we present experimental results of the MTF measurements of an IF CCD sensor. In our experiments two monochrome IF CCD sensors (one with microlences in front of the pixels, and one without) with square shaped pixels were investigated. For the measurements of the sensor MTFs the single-slit aperture modulated laser speckle method was employed. The MTF calculations were performed in the spatial frequency region ranged from zero to the Nyquist frequency. The slit of the aperture was specially designed with a square shape, which allows us to simultaneously perform the vertical and horizontal one-dimensional MTFs assessments in a single cycle of measurements. Since the pixel pitch in IF sensors are different in the vertical and horizontal directions, the corresponding Nyquist frequencies will also differ in these directions. In the vertical direction (in which the sensor has the greatest fill factor, i.e. the pixel pitch is closer to the pixel size) the Nyquist frequency is smaller then in horizontal direction. Therefore, in our experiments, to avoid aliasing effects, the aperture was placed at such a distance that the cutoff frequency in the vertical direction was equal to the corresponding Nyquist frequency of the sensor. It was observed that for the sensor without microlences, the MTFs in the horizontal and vertical directions differ, while for the sensor with microlences the behavior of the MTFs in both directions are very similar.

Finally, from the divergence of the MTF curves in the two directions, the ratio of fill factors were calculated, and it was found that the obtained results are in good agreement with the manufacturer specifications.

8073A-66, Poster Session

Degradation of the MTF of a CCD sensor at binning modes beyond the Nyquist frequency

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In recent years CCD (charge coupled devices) manufacturers have significantly increased the total number of photoactive pixels at the cost of reducing pixel sizes, and decreasing sensitivity and frame rate of a sensor. However, to overcome these drawbacks for applications where sensitivity and/or frame rate has fundamental importance the CCD manufacturers supply their devices with multi-purpose options to manipulate the sensor's readout pattern. One of these versatile abilities is a flexible pixel binning (PB) option. Briefly, PB is a process of combining multiple pixel charges in horizontal, vertical or in both directions simultaneously, into a single charge. The PB process positively influences the signal-to-noise ratio, sensitivity, and frame rate, but at the cost of decreasing spatial resolution, which, in turn, negatively influences the output image quality, i.e. the spatial frequency response of the imaging system. In this work we study the impact of PB options on the modulation transfer function (MTF), which is a classical measure for characterizing the spatial-frequency response of optical imaging sensor.

In our previous work (Nasibov, A., Kholmatov, A., Nasibov, H., et al., "The influence of CCD pixel binning option to its modulation transfer function," Proceedings of SPIE Vol. 7723, 77231A (2010).) we investigated the influence of the PB process to the sensor MTF in the spatial frequency region from zero (DC signal) to the sensor's Nyquist frequency by using the single-slit laser speckle method. In this work we have performed the experimental investigation of the modulation transfer function (MTF) of a CCD array in its PB modes beyond the Nyquist limit. The MTF measurements were performed using the double-slit aperture modulated laser speckle method in the spatial frequency range from zero to twice the Nyqiust frequency. The MTFs of a monochrome CCD sensor with 1360x1024 pixels at normal mode, and nxm (n,m={2,3,4}) PB modes were measured and the degradation factor of MTF analyzed. The obtained results are in good agreement with the therotically calculated ones, described in the our aforementioned work. Finally, this work also presents the comparative study of the sensor MTFs at normal and PB modes, measured by employing the single slit and the double slit aperture laser speckle methods.

CCD binning is widely used in spectroscopy, astronomy, night vision, chemiluminescence, and in many image processing applications, such as autofocus, object tracking, particle imaging velocimetry, etc. The results of this work can be useful for designing optical systems involving CCD PB options.

8073A-67, Poster Session

Optical gas sensor using doped polypyrrole (PPy)

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In previous works it was demonstrated that the electrical resistivity of Poli (p-phenylenevinylene) PPV, and poli(p-xylylenes) PPX changes when exposed to different organic solvents which allowed the development of applications in electronic nose [1,2]. However optical gas sensors have several advantages over conventional electronic gas sensors like high sensitivity, reduced signal noise, and compatibility with combustible gases.

The optical properties of polymer materials are of great importance in modern optical design of polymer based optical sensors and devices. Thin polymer films appear in a wide spectrum of applications such as photonics, data storage, communications and sensor devices [3]. In this work an optical sensors for the detection of gases using as sensitive materials poli (p-phenylenevinylene) PPV, and poli(p-xylylenes) PPX is proposed.

Sensor performance for different ethanol gas concentrations has been measured, and results showed a variation of the refractive indices of these polymers (approximately 0.1 RIU - Refractive Index Units) in the wavelength of 632.8 nm.

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8073A-68, Poster Session

Fiber-optic DTS system application in the research of accumulation possibilities of thermal energy in the rock mass

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The team of authors tries to provide information on the results of the fiber-optic DTS system application under long-term research of accumulation possibilities of thermal energy in the rock mass in this article. In 2006, was in Ostrava implemented the largest object in the Czech Republic, which is heated by heat pump system. It is a multi-purpose aula at V B-TU + CIT (Centre for Information Technology). The installed heat pump system consists of ten heat pumps with a total output of 700kW and 110 wells about 140m deep. The applied research is conducted in two measuring polygons ("Big" and "Little" polygon). Simultaneously with fiber-optic DTS system is applied group of PT1000 temperature sensors and Geotermal Response Test (GERT). Fiber-optic DTS system is deployed inside polyethylene PE collector via a special sensory fiber optic cable. The ecological antifreeze mixture, based on the technical spirit, used for the collection and delivery of energy to the rock mass circulates inside of PE collector. PT1000 temperature sensors are placed at certain intervals on the outer side of the PE U-tube within the heat well. The result of application of the fiber-optic DTS system is information about the heat profile of wells, thermal conductivity of the geological environment and the impact of external changes in the thermal wells, along with the accumulation possibilities of thermal energy in the rock mass (over-summer period).

8073A-69, Poster Session

Spectral characteristics of thermal radiation emitted in the optical fiber as a method of high temperature measurement using fiber optic sensor

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In measurement engineering is generally starting to show trend of passage from standard measurement devices to the new devices. This trend is based on the overall progress of technology of optical fibers on one side and also the technical requirements for better, more accurate measurements on the other side. An ideal measuring device meeting the both requirements are Fiber optic sensors. As an innovative can be considered high-temperature measurement using Fiber optic sensors. The principle of this sensor is based on black body radiation. Temperature dependence can be evaluate in two ways. The first method is to evaluate the total power radiated from such a sensor. The second method is based on concentrating on the spectral characteristics that arise in such FOS, this method will be described in the following article.

8073A-70, Poster Session

Measurement of the spectral characteristics of telecommunication fiber emitted at high temperatures

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The fiber optic sensors have a great future thanks to its sizes, features and usage possibilities in measurement engineering. Optical fiber is mostly used as medium for the transfer of information, but if we consider a optical fiber as a sensor then the other usage can be found for example in medicine or biology. If the optical fiber is heated by sufficiently high temperature, the light signal starts to be emitted in the internal structure. This signal has a spectral characteristic, which can be used for for evaluation of temperature thanks to quality analysis. The article will describe the evaluation of spectral characteristics for utilisation as fiber optic sensor for very high temperatures.

8073A-71, Poster Session

Optical chemical sensor for putrescine determination

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Biogenic amines (BA) are organic bases that are generated by microbial spoilage of food high in protein content (meat and dairy products, fish etc.). The presence of BA in food constitutes a potential public health concern due to their physiological and toxicological effects. Increased amounts of BA may be found in food as a consequence of the use of poor quality raw materials, contamination and inappropriate conditions during food processing and storage (temperature, moisture). Thus, the determination of BA in food is important for two reasons: the first is their potential toxicity; the second is their usage as indicators of the degree of freshness or spoilage of food [1]. Currently used microbiological methods for the detection of microbial spoilage give adequate results, but are time consuming.

Growing interests of the meat industry for rapid and accurate detection systems for microbial spoilage of meat and meat products recently opened new possibilities for development of specific optical chemical sensors. The use of optical chemical sensors, as part of intelligent packaging, represents a new approach and guideline for food safety.

In this study, we represent the development of sol-gel based optical chemical sensor for detection of target biogenic amine putrescine in poultry food products. Different acid- and base-catalyzed sol-gel procedures were studied for the preparation of thin sol-gel films on glass and PET foil slides. New sol-gel matrix has been developed for the rapid detection of the putrescine level in the samples. The effect of the content of organically modified sol-gel precursor in sensor layer was studied. Colorimetric based indicator was used to exhibit strong color change in presence of putrescine. Sensor had to meet key requirements, such as broad working range, temperature dependence at - 4 °C, rapid response time, photochemical and adequate mechanical stability, no intrinsic toxicity and biocompatibility [2]. All layers were tested in terms of sensitivity, response time, detection limit, dynamic range, regeneration and selectivity. The stabilities of sensor layers were also evaluated according to directive (EC) 1935/2004. The sensor layers showed significant signal changes and color changes from red to yellow on exposure of putrescine. They showed response and recovery time in few seconds. The lower detection limit was 5 μM of putrescine and the upper detection limit was 2, 5 mM of putrescine. The reversibility of sensor was also reached.

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8073A-72, Poster Session

Attenuation changes measurement for SM fiber optic splitters in dependence on temperature

P. Siska, J. Látal, P. Koudelka, F. Hanáeck, J. Vitásek, J. Skapa, V. Vasinek, Technical Univ. of Ostrava (Czech Republic)

The article describes the attenuation changes with temperature of commercially available singlemode fiber optical splitters and its capabilities for internal use. Effects of temperature were simulated using a special bath and attenuation changes for each branch of the splitters were observed. Temperature measurement range starts at 20 °C with increments of 5 °C and grew up to the 70 °C. Each fiber splitter was measured from all directions and several times in order to construct the statistical evaluation of the measured and calculated data. The measurement content also included determination of attenuation, crosstalk between the branches, insertion loss and total loss.

8073A-73, Poster Session

Multiplexing FBG-based sensors using unmodulated continuous wave DFB diode laser

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Fiber Bragg Gratings (FBGs) have become one of the most popular types of multiplexed fiber optic sensors. They have been recognized to meet well the criteria for large sensor networks. Many different techniques for multiplexing FBG-based sensors have been demonstrated. The most common are based on WDM and TDM methods. Also, so called Code Division Multiplexing has been demonstrated. Usually, a light source is modulated by a special code represented by a pseudorandom bit sequence and de-multiplexing of signals from different sensors can be performed by calculating auto-correlation function using different delayed version of the code.

In this paper we present a very simple and inexpensive technique capable to interrogate multiplexed ultra-weak Bragg gratings written in a long SMF-28 fiber. The technique is suitable for distributed detection and localization of alarm conditions in early warning systems for pipeline leak monitoring, linear temperature sensors for fire detectors, etc. It is based on measuring cross-correlation between the noise-like probe signal coupled to the sensing fiber and the signal reflected back. A DFB diode laser operating in a CW regime was used as a light source. DFB diode lasers possess usually a low level of intensity noise. In our scheme, we make a use of inherent phase noise of the diode laser to generate a noise-like broadband probe signal. For effective conversion of the phase noise into intensity noise, we used a long unbalance interferometer with the arm length difference of 100 meters. A random-intensity-modulated light signal at the interferometer output had a sufficient bandwidth and power to be used as a probe signal in the correlation detection scheme.

We present results of experimental verification of this technique in different sensor configurations for static strain and vibration measuring. Multipoint sensor using Bragg gratings with reflectivity of 0.01% printed in a 3-km long fiber was demonstrated. The paper discusses main features and limitations of the approach.

8073A-74, Poster Session

Mesoporous nano-thin film modified fiber optic long period grating sensor for chemical sensing

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A fibre optic long period grating (LPG) with an nano-assembled mesoporous coating of alternate layers of poly(diallyldimethylammonium chloride) (PDDA) and SiO2 nanospheres was used for the development of a highly sensitive fibre-optic chemical sensor. Sensor fabrication involves a 2-stage process: firstly, the deposition of the base mesoporous thin film (PDDA/SiO2) over an LPG written in the optical fibre using a layer-by layer technique, followed by the infusion of a functional material, in this case a porphyrin compound (tetrakis-(4-sulfophenyl)porphine, TSPP), into the porous film. The refractive index of the base mesoporous coating, determined at a wavelength of 633nm using ellipsometry, was found to be 1.2. The infusion of TSPP into the coating resulted in a significant change in the RI of the coating, producing a dramatic change in the transmission spectrum of the LPG. As TSPP is known to exhibit changes in its transmission spectrum, and thus refractive index, when exposed to ammonia, the sensing of ammonia in aqueous solution was chosen as an example to demonstrate the sensing principle of the LPG sensor. The device showed high sensitivity to ammonia with a response time less than 100 s and a limit of detection of 140 ppb. The sensing mechanism was additionally studied using same PDDA/SiO2 films infused with the TSPP deposited onto the quartz crystal microbalance (QCM) electrodes and quartz substrates. The UV-Vis and QCM measurements revealed that TSPP is incorporated into mesoporous PDDA/SiO2 film via electrostatic interaction. Exposure of the functional film to ammonia results on partial deprotonation of the TSPP and resulting desorption from the film, which in turn leads to the decrease of its refractive index.

8073A-75, Poster Session

Optical sensor fabrication based on nano-assembled thin films for skin gas assessment

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An evanescent-wave optical fibre sensor modified with tetrakis-(4-sulfophenyl) porphine (TSPP) and poly(allylamine hydrochloride) (PAH) bilayers using layer-by-layer (LbL) electrostatic self-assembly was tested to measure the gas emitted from human skin. Optical intensity changes at different wavelengths in the transmission spectrum of the porphyrin-based film were induced by the human skin gas and measured as sensor response. Influence of relative humidity, which can be a major interference to sensor response, was thoroughly studied and shown to be significantly different when compared to the influence of skin emanations. Sensor response to humidity is linear only in the 400-480 nm spectral region and this could be employed for simultaneous humidity control when testing skin exhalations. The senor response to human skin emanations that contain mostly water, however, was different and more complex as compared to humidified air and can be explained by the presence of additional volatile compounds in the emanations. While tested on several humans, the sensor showed a capability to distinguish skin emanations from different people and some changes in their physiological conditions by applying the pattern recognition technique (PCA). This approach enabled to distinguish skin odors of different people and their altered physiological conditions after alcohol consumption. Responses of the current optical sensor system could be considered as composite sensor array, where different optical wavelengths act as channels that have selective response to specific volatile compounds. In such representation our system have a significant advantage in size, simplicity of fabrication and cost as compared to the arrays of chemical sensors or more sophisticated GC techniques. Being able to recognize qualitative changes in “global body odour” the described system can receive a chance to be applied in healthcare for disease diagnostics.

8073A-76, Poster Session

Multispectral photoplethysmography biosensor

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Multi-spectral photoplethysmography (MS-PPG) biosensor is intended for analysis of peripheral blood volume pulsations at different vascular depths. The light penetration depth in skin varies depending on wavelength - for example, green light penetrates only Stratum corneum and epidermal layer (till 0,2 mm), but red and infrared radiation penetrates also in dermal layer (till 2 - 3 mm).

The newly developed optical fibre biosensor comprises one multi-wavelength laser diode (405nm, 660nm and 780nm) and a single photodiode with multi-channel signal output processing and built in Li-ion accumulator; special software was created for visualisation and measuring of the MS-PPG signals. ARM7TDMI-S LPC2148, NXP (founded by Philips) 32 bit processer with bit rate 60 Hz performs receiving and measuring of the signal. Power supply voltage is stabilized with built in current equalizer. COM-USB junction was used for transportation of the captured data from device to computer. Red and IR wavelengths radiation output can be changed in the interval 90 - 280 μW, while the blue radiation output is kept constant. Device does not include analogue amplifier and filters since a new digital PPG measuring approach is used. The signals acquired from measuring photodiode discharge time which is inverse to absorption. The biosensor operates in contact reflection mode, with simultaneous parallel recording of PPG signals at each wavelength. Analysis of the MS-PPG signal shapes and baseline variations at three wavelengths provides information on haemodynamic parameters at different vascular depths and could be useful in dermatology for assessment of skin damages and pathologies.

8073A-77, Poster Session

Noise reduction of FBG sensor signal by using a wavelet transform

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We developed a fiber-optic multi-stress sensor system for the use of monitoring possible abnormal high-temperature or acoustic vibrations in electric power systems. This hybrid sensor system consists of a fiber-optic Sagnac loop with FBGs (fiber Bragg gratings) and fiber coils wound around cylindrical mandrels in it. A fast wavelength-scanning, in the wavelength range of 1520~1570nm, fiber laser is used as a light source. Although the output level is strong enough because of the high output power density of the fiber laser, it is difficult to separate the FBG signals from the interference signals of the fiber coils, making it difficult to obtain high signal-to-noise ratios for the FBG sensors. Moreover the output drifts of the wavelength tunable laser generate a lot of intensity and coherence noises in the Sagnac interferometer. To suppress these noises and extract FBG sensor signals, we propose to use a Gaussian curve-fitting and wavelet transform. Wavelet transform is a signal processing based on a windowing approach of extended ‘scaled’ and ‘shifted’ wavelets, and has been applied to a wide range of engineering applications. Recently, wavelet transform has got public interest as an efficient way of signal processing in structural health monitoring systems because of its feasibility over Fourier transform (FT) which has been widely used in many applications. In our system, the output from the fiber-optic sensor system is wavelet transformed first to minimize the coherence noises from the Sagnac interferometer and then Gaussian curve-fitted to compensate for the Bragg reflection spectra deformation. The degree of denoising can be adjusted by setting an appropriate threshold value in the process. The feasibility of the wavelet transform denoising process is presented with the experimental results, which showed much better accuracy than the case with only the Gaussian curve-fitting algorithm.

8073A-78, Poster Session

A fiber-optic Sagnac multi-stress sensor system

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We constructed a fiber-optic sensor system with a Sagnac loop. Several FBGs (fiber Bragg gratings) and a fiber coil wound around

a cylindrical mandrel are placed in the single Sagnac loop for the measurement of temperature and vibration in electric power systems, respectively. The Bragg reflection spectra which convey the quasi-distributed temperature information are analyzed by using a volume phase grating spectrometer. From the photo-detector array output, temperature-induced peak movements are traced by using peak search algorithm which uses Gaussian curve-fitting to compensate the possible deformation by external tensile stress. Because the FBGs are placed in the Sagnac loop and their signals are mixed with the output of the acoustic sensor, it is difficult to distinguish the Bragg reflection spectra from the photodetector signal. For efficient demodulation of the FBG sensors, an optical attenuator was placed near by the fiber-optic directional coupler and a differential amplifying signal processing was used. Because acoustic sensor gets the same attenuation from the both direction, it doesn't affect any influence to the acoustic sensor signal. For the feasibility test of the FBG sensors, one of the FBGs was placed in the temperature chamber, and the temperature was changed periodically. For acoustic sensing, an acoustic field at a specific frequency was generated by using a PZT (piezoelectric transducer) vibrator. The FBG signals are analyzed by using a volume phase grating spectrometer demodulation and the acoustic signals are analyzed by using a FFT spectrum analyzer. By configuring the two kinds of sensors in the same Sagnac loop, multi-stress sensing is possible with a lot less cost and much simpler structure. With the preliminary experimental results, we confirmed the feasibility of this multi-stress fiber-optic sensor system for the possible uses in integrity monitoring of the high-voltage electric power systems, such as transformers.

8073A-79, Poster Session

Comparison of surface chemistries for protein immobilization onto NH2-rich surfaces

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Immobilization of functional molecules on the surface of a sensor presents a crucial step in the development of an affinity biosensor with direct impact on performance characteristics of the sensor such as sensitivity, specificity and limit of detection. In this work, six different approaches to the immobilization of proteins on NH2-rich surfaces are investigated and compared using surface plasmon resonance (SPR) biosensor technology.

The amine terminated alkanthiol (NH2-AT) self assembled monolayer (SAM) and the poly(L-lysine) polymeric layer (both with well-defined surface structure and properties) were used as foundation layers for the immobilization of proteins. These two different foundation layers were combined with the electrostatic and covalent binding of proteins. The covalent binding was performed by the amine coupling with NH2-AT or by photochemical attachment of protein to the NH2-AT.

The immobilization approaches were evaluated for the immobilization of model proteins, such as antibody against the human chorionic gonadotropin. The resulting biomolecular assemblies were characterized using an SPR sensor and characteristics in terms of the density of receptors, binding efficiency and the level of non-specific adsorption.

8073A-80, Poster Session

Advancing surface plasmon resonance (SPR) sensors towards single molecule detection

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Label-free detection of low levels of chemical and biological analytes presents an important goal for modern bioanalytics. In this work, we explore the surface plasmon resonance (SPR) method with respect to feasibility of detecting a single molecule. We have developed an SPR sensor with the size of the detection area reduced to the physical limits given by the diffraction limit and the propagation length of a surface plasmon (approx. 1.5 x 30 microns). In the SPR sensor, light from a high spectral density light source (superluminiscent diode) is coupled to a surface plasmon using a shallow diffraction grating. The use of a grating allows us to employ a high-magnification microscope objective. In order to characterize detection properties of the sensor a protein monolayer was formed in the sensing area and detected by the SPR sensor. Experimental results suggest that the sensor is capable of detecting as few as hundreds of protein molecules.

8073A-81, Poster Session

Pixel diamond detectors for excimer laser beam diagnostics

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The technology of laser beam profiling in the UV spectrum of light is evolving with the increase of excimer lasers and lamps applications that span from lithography for semiconductor manufacturing in VLSI and MEMS technologies, to laser-cutting, from eye surgery to dermatological treatment. Indeed, to improve emission performances, fine tuning of the laser cavity is a mandatory requirement. In such a field, the development of a beam-profiler, able to capture the single excimer-laser pulse and process the acquired pixel-signals in the time-period between each pulse, is mandatory. Offering unique properties in terms of thermal conductivity and visible-light transparency, diamond represents one of the most suitable candidate for the detection of high-power UV laser emission. The fast diamond photoresponse, in the ns time regime, suggests the suitability of such devices for fine tuning feedback of high-power pulsed-laser cavities, whereas the material solar-blindness guarantees high performance in UV beam diagnostics also under high intensity background illumination. The relatively high resistivity of diamond in the dark allowed the fabrication of photoconductive detectors with a vertical structure of the pixels. 10 mm x 10 mm MWCVD diamond specimens, 200 ÷ 300 μm thick, were selected for the present study, cleaned by dipping in hot sulphochromic solution and rinsed in aqua regia. Sandwich contacts were realized by evaporating silver on the top and bottom faces of the diamond films by thermal evaporation. The thickness of the bottom electrode, used for device biasing, was 100 nm, whereas the top contact was only 50 nm thick, in order to be semi-transparent to the impinging UV light. Standard photolithography was used to define the array structures: the 1D detector consisted of a multistrip structure with 32 fingers, 5 mm in length, 80 μm wide; the 2D detector was a 64-pixel array (500 μm x 500 μm each). For excimer laser beam monitoring measurements, sensor pads were wire-bonded to a dedicated "daughter"-board where the front-end electronic circuits, based on the DDC11X current input analog-to-digital converters, were also mounted. In particular, each pixel of the sensor was conditioned by a dedicated electronics in which a high-precision switched capacitor integrator was followed by a high-resolution 20 bit sigma-delta analog-to-digital converter. A computer-interface main board was designed to include the circuitry used to control the front-end daughter-board and the interface to a personal computer (PC) for data transfer. The interface-board had the capacity to collect the samples converted from each channel to be downloaded to the PC. Moreover, depending on user's preferences, the digital-control circuitry established the integration time of analog integrators in the 50 ÷ 1000 μs range for the on-board clock frequency of 10 MHz. Satisfying the single excimer pulse acquisition requirement, the overall 500 μs conversion time allowed a data throughput up to 2000 samples per second, enabling a real time diagnostics of the UV source.

8073A-82, Poster Session

Selected aspects of mid-IR optopair-based gas detecion and analysis in a wide concentration range

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Paper presents important aspects of optopair LED - PD (photodiode) realised optoelectronic system for gas analize in wide concentration range. Based on main parameters: radiation flux, optical power, heterostructire quantum efficiency, temperature dependences we describe main aspects that shold be mature. We also describe solutions of this aspects present system for methane analize in wide concentration range. We also present short description of the obtained results.

8073A-83, Poster Session

Creation of biosensor platform based on localized plasmon resonance in glasses with silver nanoparticles

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SPR biosensors (BS) are known to become a central tool for characterizing and quantifying biomolecular interactions [1]. The number of publications reporting applications of SPR BSs for detection of analytes related to medical diagnostics, environmental monitoring, food safety has been rapidly growing. One of an alternative to conventional SPR BSs are sensors based on localized surface plasmon resonance (LSPR). The main advantages of LSPR BSs are high efficiency, low expense of biological material (analyte), independence of SPR wavelength, good perspective for invasive using and biochips creation, possibility for waveguide technology and label - free detection technique. Glasses with silver nanoparticles (NPs) are good candidates for creation of LSPR BSs with planar waveguides circuits as for excitation as for detection of plasmon resonance shift [2]. We are designing the BS platform based on silver NPs in photothermorefractive (PTR) glasses [3] with planar plasmonic waveguides. The patented technology of silver NPs forming in subsurface glass layers consists of electron beam irradiation and subsequent thermal treatment of the special smelting PTR silica glass.. It is shown the metallic nanoparticles can be obtained either directly during electron irradiation or after the thermal treatment. The HRTEM (JEM 2100F, JEOL) measurements demonstrate the nanoparticles form discrete layers parallel to the glass surface. Nanoparticles size is about 5-10 nm, while the concentration in a layer reaches 6·1016 cm-3. The extinction spectra analysis in accordance with Mie model is in a good agreement with size distribution obtained from HRTEM images. The model of individual silver NP and layers of NPs formation in PTR glasses is proposed.

The peculiarities of LSPR effect appearance at different dozes of electron beam irradiation and thermal treatment conditions are optically investigated. The beginning stage of thermal treatment of electron beam irradiated samples leads to appearing of the peak at 400 nm related with plasmon resonance in silver NPs. The subsequent thermal treatment carries the red shift of the resonance to 440-450 nm.

Immobilization of D-galactose/D-glucose binding protein (GGBP) on top of PTR glass as a BS test was realized successfully. The fluorescence enhancement in range 540-630nm in presence of D-glucose was obtained in acrylodan dye with GGBP-W183C.

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8073A-84, Poster Session

Formation of TH- and TE-polarized Bessel light beams at acousto-optic diffraction in anisotropic crystals

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One of the most important areas of investigations of Bessel light beams is the development of methods of their parameters manipulation. Particularly, the methods of dynamic optical manipulation of polarization state and spatial structure of a higher-order Bessel beams among them the formation of TH- and TE-polarized beams are of great importance. This is of great interest for application in systems for recoding/ reading information, microscopy, and also for manipulating microparticles.

In the report a method has been proposed for transformation of polarization state of Bessel beam in the process of acousto-optic ( ) interaction in uniaxial crystals. To realize the polarization transformation, the input Bessel beam with circular polarization falls on the crystal in the direction of optical axis. A plane ultrasonic wave propagates also in parallel to the optical axis. Circularly-polarized beam excites TH- and TE-polarized eigen waves in crystal. The process of AO interaction has been described using equations for coupled modes. The peculiarity of these equations in comparison with the case of plane waves is the presence of two parameters describing so called transverse and longitudinal synchronisms. The longitudinal synchronism is described by wave detuning, transverse one by the overlapping integral of Bessel beams. The case has been studied when AO interaction is realized only in the channel that leads to the change of the direction of TE-beam propagation into reverse and spatial separation of two modes. Consequently, due to AO interaction the formation of TE- and TH- polarized Bessel beams is possible from initial circularly-polarized beam. In conditions of full transverse and longitudinal synchronism the efficiency of AO process can be close to 100%. The advantage of the proposed method is the possibility of managing the efficiency of AO diffraction due to which generation is possible of various superpositions of TE- and TH- Bessel beams.

8073A-85, Poster Session

Photoluminescence properties of anodic alumina for application in optical sensors using SERS

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Anodic alumina (AA) preserves great potential possibilities when creating photon and opto-electronic structures of optical sensors. One of the important areas of AA application is the formation on their basis of optical sensors using surface-enhanced Raman scattering (SERS) in which metal nanoparticles have definite size, configuration and homogeneous distribution. Optical characteristics, particularly AA luminescence background, can contribute essentially into SERS spectra. That is why in the paper AA photoluminescence properties and optimal conditions of oxide formation for constructing on their basis of optical sensors have been studied. The influence of electrolyte on the intensity and position of bands in spectra of AA luminescence has been considered. AA luminescent properties of fabricated in the solutions containing oxalic, sulfuric and phosphoric acids and their combinations have been studied. The alumina photoluminescence in the region of 450-500 nm is shown to be determined by anions of oxalic acid. The F+ centers are responsible for the luminescence band at 390 nm. AA photoluminescence formed in the solution of sulfuric acid in the range of wavelengths of 350-800 nm is determined by divacancies of oxygen with various charge states (F2, and centers). Sulfate ions do not influence substantially the luminescent properties of AA in the spectral region under study. Intensity of photoluminescence is practically in order higher that in AA formed in oxalic-acid electrolyte. The content of anion impurities of electrolyte determining photoluminescence in AA is proved by the data of thermogravimetric investigation and IR-spectroscopy. The results are given of comparative analysis of water and anion impurities content, temperature of elimination of electrolyte anions at oxide heating up to 10000C. Quantity of implemented into the oxide structure of anions of electrolyte is higher for AA obtained in sulfuric-acid electrolyte in comparison with oxalic-acid one and is 9,9% instead of 7,6% from the total mass. For oxide obtained in oxalic-acid electrolyte lower value of high temperatures of elimination of impurities and crystallization has been determined. The change of bands intensities typical for vibrations of carbonate-carboxylated, hydroxyl, sulfate groups, IR-spectra of annealed oxide also conforms to the results of thermogravimetric and photoluminescent analysis. For intensity reduction of photoluminescence AA oxide is to be annealed at the temperatures of ≤ 800 , and for using in sensors on the basis of SERS it is reasonable to use electrolyte on the basis of sulfuric acid.

8073A-86, Poster Session

Fiber-optic multi-point temperature sensor for oil industry

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Fiber-optic sensors (FOSs) have ability to work at influence of intensive electric and magnetic fields, firmness to excited environments, explosion safety, not less important advantage is possibility of creation of the distributed (multi-point) measuring systems on their basis. It means that the same fiber-optic sensor can be used for performance of measurements in a considerable quantity of space points. Thus the obtained data is transferred in the form of spatial distribution of the corresponding measured value.

Practically unalternative use of a FOS is the control of physical parameters directly in a groove in the oil-extracting industry. As one of examples of application of similar systems their use during extraction extra-heavy crude so-called bitumen oil. The contents in oil of a plenty of gummy and paraffinic connections does makes its viscous and inactive, that causes of carrying out of special actions for its extraction on a surface and the subsequent transportation. Extraction high-viscosity oil is connected with application of the overheat pair, the petrosated layer applied a local warming up. Temperature monitoring allows to determine optimum time of extraction warmed-up viscous oil.

The new structure of the multi-point fiber-optic temperature sensor intended for in-situ thermometry at extraction of high-viscosity oil is presented. We consider that high sensitivity of recirculation frequency in closed optoelectronic system to small external influences on fiber optic path will allow to realize a new principle of frequency representation of the information. Thus increase of measurement accuracy will be reached by identification of measured physical parameters on recirculation frequency of a single optical pulse with its periodic restoration on amplitude, the form and duration on each cycle of circulation. Fiber-optic sensor was constructed as a closed optoelectronic contour formed by a set of injection lasers, multiplexer, an optical fiber delay line, spectral reflective elements, demultiplexer, photoreceivers, threshold device and regeneration block. In result in one fiber some wavelength division multiplexing information recirculation channels are formed. The principle of measurements is based that temperature influence leads to change of length and refraction index of a fiber. The action principle is based on registration recirculating frequency of single pulses with their periodic regeneration on various wavelengths. Sensitive elements are sections of an optical fiber with the metal covering, divided spectral-selective reflecting elements. Using dichroic mirrors as spectro-selective reflecting elements has following advantages: a) as radiation in dichroic mirrors practically is not absorbed, they can work at the high density of light energy; b) possibility to work at enough high environment temperature (to 500ºC) without fusion and deformation; c) due to the design, they possess considerable time of operation without degradation of spectro-selective properties; d) because of that dichroic mirrors have a wide spectral band of reflection, there is no necessity to use special measures on stabilization of spectral characteristics of semiconductor lasers. The error of temperature measurements does not exceed 0,3°C at measurement time 1 s in a temperature range from 0°C up to +250°C, and the maximum length of the fiber-optic measuring converter reaches 5 km at use multimode gradient optical fiber.

8073A-87, Poster Session

Cyclops opening-up fiber for real-time fluorescence sensing

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Compared with traditional fluorescence-based microstructured fiber sensors using filled structure, the opening-up microstructured fibers have shown many advantages for real-time sensing. The design and theoretical study about Cyclops opening-up microstructured fiber is present in this paper. In Cyclops fiber, a large asymmetry hole is placed in fiber cladding. A tri-hole design is adopted for fiber core to enlarge the evanescent field interactions with measured material. This structure is compatible with the traditional stack-draw processing. To make the opening-up structure, chemical etching (with acid) or polishing machining could be used for the asymmetry hole.

The opening depth and shape of large asymmetry hole is important for real-time sensing response in Cyclops opening-up fiber. The relationship between marching depth in cladding and fluid concentration distribution at different time in evanescent field near fiber core is analyzed numerically based on incompressible Navier-Stokes equations and finite element method (FEM). The results show that the concentration distribution in evanescent field adjacent to fiber core can reach the true value out of cladding below ten seconds by design cladding structure appropriately. The field distribution of fundamental mode and some cladding mode of Cyclops fiber without tri-hole core and with different tri-hole are presented in this paper too. To analyze the sensing error in distributed measurements, the difference in effective index, dispersion parameter and confinement loss about two fundamental non-degenerate modes of the Cyclops fiber are studied. Cyclops fiber show good characters in these aspects compared with wagon wheel (WW) opening-up fiber. In order to evaluate the performance of sensing based on Cyclops opening-up fibers we adopted the modal power fraction (PF) within the sensing region and the effective modal area (Aeff) and the fluorescence capture fraction (FCF). The results show the Cyclops opening-up fiber is a competitive candidate for real-time fluorescence sensing.

8073A-88, Poster Session

A large-scale strain sensor based on fiber Bragg grating

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Fiber Bragg grating (FBG) have an extensive use in the field of optical sensing. As a sensing cell, it can transduce physical quantities like strain, temperature, etc, having attractive merits of being small and light, resistance to corrosion and immunity to electromagnetic interference, etc. Commercial FBG strain sensor has a sensing range of no more than 9000 (0.9%), however, larger-range strain sensor is demanded suiting for special demands in industry such as heavy structural distortion and crack happening. A new kind of large strain sensor based on FBG is studied here. The sensing element has a metal trapezoidal frame. The two feet of the frame can sense a large strain of the body, which is converted to a small strain of the trapezoidal frame' beam. FBG, attached to the beam surface, senses the small strain, and then the body's strain can be known from the FBG's wavelength shift. The trapezoidal frame is taken theoretically analysis adopting the 'unit load method' and numerical simulation by finite element method, and an excellent linear relationship between the body's strain and the FBG's wavelength shift is obtained. The sensitivity model of the sensor is described also. Real large strain sensors are homemade, with verifying sizes of the frame and FBG. The large strain is given by an electrical-controlling move apparatus, and the FBG's wavelength shift is interrogated by MOI sm125 instrument. The experimental results show an outstanding large-strain sensing ability of the sensors, having the sensing range of -16~33.3%, with the linearity of less than 0.9%, the hysterisis error of less than 0.9% and the repeatability of less than 1%. These sensing performances are discussed in detail, in order to improve them.

8073A-89, Poster Session

Properties of Bessel beams in the structure containing a layer of metamaterial

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The properties of Bessel light beams (BLBs) propagation and transformation on the boundary of the usual medium and metamaterial and in the structure, containing a layer of metamaterial, are studied. The reflection and refraction coefficients of arbitrary Bessel beam are represented as superposition of linear combinations of reflection and refraction ones of - and - polarized Bessel beams. It is established that during crossing the boundary of the usual medium and metamaterial the change of directions of energy flow rotation and orbital angular momentum of a high-order Bessel light beam on the opposite one takes place. It is shown that when arbitrary polarized BLB crosses this boundary, circular polarized components, forming the beam, change the rotation direction. It causes the transformation of polarization state of BLB. The possibility is established and conditions are determined for unidirectional and opposite directional propagation of Bessel light beams phase and the longitudinal component of its energy flux in metamaterials.

A theory of generation of evanescent Bessel light beams into the structure containing two semi-infinite media, separated by a layer of metamaterial, has been developed. The exact solution is presented of the problem of tunneling vector BLBs (TE and TM modes and their linear superposition) through the layer surrounded by various dielectric media. Correct analytical expressions have been obtained for the field forming into and out of the layer. Longitudinal and transversal (azimuthal and radial) energy fluxes densities, existing into the structure, have been calculated. Their dependence has been established on the correlation between refraction coefficient of input into the structure media, and also polarization of incident beam. The possibility has been found out and conditions have been determined of strengthening Bessel light beams. It has been established that into the layer the evanescent BLBs, generated by both TM modes and circularly polarized incident Bessel beams, have first maximum in radial distribution of longitudinal projection with lateral width much less than the wavelength. It has been found out that for the case of circular polarized incident Bessel beam unlike TM mode in radial distribution of z- projection of Pointing vector, areas appear, for which the longitudinal energy flux in the layer is opposite to the direction of propagation of incident BLB.

Obtained results can be used for development and optimization of techniques and devices for testing quality of surface of various substrates and in near-field optical microscopy with sub-wave resolution.

8073A-90, Poster Session

Fabry-Perot resonator as an optical sensor

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Optical sensors have been attracting many researches for their broad applications in fields of chemistry, biology, biochemistry, environment, and medical care. Sensing techniques applied in those optical sensors include waveguide mode sensor [1], surface plasmon resonance (SPR) sensor [2], fiber Bragg grating sensor [3], long period grating sensor [4], and Fabry-Perot interferometer senor [5]. A serious drawback of the waveguide mode sensors based on the technologies of double prism coupling, single prism coupling, and grating coupling is that the probe efficiency is relatively limited, since merely a few percent of the mode energy propagates in the sensing medium [5]. In SPR sensors a considerable part of the mode energy propagates through the lossy metal layer resulting in a relatively wide resonance dip in the reflectivity.

In the present work we propose theoretically two high sensitivity optical sensors based on Fabry-Perot resonance mode and fringes of equal thickness structure. In the first structure, we assume Fabry-Perot interferometer with a piezoelectric material stands as a substrate. The sample to be analyzed is localized in the core region between the interferometer mirrors. The thickness of the sample is controlled by the potential difference applied to the piezoelectric substrate. For any sample refractive index change, the resonance potential difference at which the reflectivity dip occurs changes. Thus the applied potential difference across the piezoelectric can be treated as the probe for detection any change in the refractive index of the sample. In the second structure, we assume the sample to be a thin film with varying thickness between two inclined partially reflecting mirrors. The number of equal-thickness fringes per unit length in the interference pattern can be used as the probe for any changes in the refractive index of the sample.

The resolution of the proposed sensors is found to be of order 3.6×10-8 and 2.2×10-7 refractive index unit (RIU) which is considerably high resolution.

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8073A-91, Poster Session

PIN photodiode bandwidth optimization in the integrated CMOS process

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Abstract- In this work, the PIN photodiode optimized for blue ray is fully integrated with standard 0.35um CMOS process and the bandwidth dependency upon thermal process and epitaxial material is investigated. It was found that the additional substrate thermal process can improve bandwidth for blue & red light but reduce bandwidth for infra-red. This is because the boron in substrate diffuse out into the intrinsic region and reduce the depletion region. And therefore the carriers generated within depletion region by blue and red move faster and carriers generated outside depletion region by infrared need diffuse longer distance before reach depletion region. And it’s also found that higher level p-type epi doping don’t impact bandwidth for blue light but reduce bandwidth for red and infra-red. That’s because higher p-type doping in intrinsic region also further reduce the depletion region. Blue light goes into silicon very shallow and the carriers still generated within the depletion region. Therefore, the carriers has very fast draft transport. As the depletion region reduced, the carriers generated by Red and Infrared at deeper silicon locate outside the depletion region and travel with slower diffuse process.

The design of photodiode should optimize the depletion region and reduce the carrier travel time.

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8073B-100, Session 10

Preparation and characterization of microstructured silica holey fibers filled with high-index glasses

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Silica based microstructured holey fibers offer the possibility for filling with unconventional fiber materials. Of special interest are chalcogenide glasses or heavy metal oxide (HMO) glasses due to their high refractive index and their nonlinear optical properties. We demonstrate two types of fibers: an index guiding fiber type with high-index glass core and silica cladding and a fiber with silica core surrounded by a periodic, hexagonal high-index glass structure giving antiresonant guiding properties. We prepared such fibers filled with arsenic sulphide glass and HMO glass by a pressurized infiltration technique. The manufacturing process is modelled on the basis of viscous glass flow parameters and is compared with experimental results obtained from the filled fibers. The propagation and spectral transmission properties of such fibers are measured and discussed.

8073B-101, Session 10

Supercontinuum generation in microstrustured tellurite fibers

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The first report of broadband supercontinuum (SC) generation in microstructured optical fibers (MOF) has brought a solution to avoid the complex construction of mid-IR sources and to lower their price. This type of fibers has generated broad interest due to their unique guidance properties, high nonlinearity and dispersion management.

We report here the fabrication and the characterization of a tellurite TeO2-ZnO-Na2O (TZN) MOF with a suspended core for infrared supercontinuum generation. Because of the disadvantages and of the excess of optical losses generally induced by the 'stack-and-draw' technique in the fabrication of soft glasses MOFs, we have processed the preform through a mechanical machining, which is quite versatile and allows to control the fiber geometry.

Using the scanning electron microscope (ESM) image of a core-section of the fiber, we extract the fiber's geometrical parameters and we compute the dispersion curve to obtain the fiber zero dispersion wavelength (ZDW). The diameter core of the fiber is 2.2 µm. The numerical predictions of the chromatic dispersion show that the profile of our MOF allows to shift the ZDW to 1.45 µm.

We have measured the spectral attenuation of this fiber and the typical attenuation curve shows a minimum of losses of 6 dB/m at 1,55 µm. Despite this level of losses, supercontinuum generation has been obtained in a 58 cm long sample of this TZN suspended core fiber. The pump was a fibered laser source delivering 100 fs pulses at 1.56 µm, allowing the pumping of our fiber in its anomalous dispersion regime. At the same time we have performed numerical simulations based on the well-known split-step Fourier resolution of the generalized nonlinear Schrödinger equation. The model takes into account the numerical chromatic dispersion and experimental losses. It also includes Kerr, self-steepening and Raman terms based on previous studies of tellurite glasses. The nonlinear Kerr coefficient deduced from numerical calculation is gamma = 437 W- 1km-1 and the effective area of the fiber at 1.56 µm is Aeff = 3.5 µm².

Numerical predictions confirm the experimental spectrum for three different input pulse energies. These spectra reveal a typical SC development which is connected with the dynamics of soliton propagation and break-up in the anomalous dispersion regime. Namely, the initial stage of self-phase modulation is followed by pulse break-up and a subsequent soliton self-frequency shift (SSFS) towards longer wavelengths owing to intrapulse Raman scattering. Moreover, by pumping close to the ZDW, solitons generated in the anomalous dispersion regime shed energy into dispersive waves (DW) in the shorter wavelength range. We show that SC spectral broadening, as induced by both SSFS (long-wavelength edge) and DW generation (short-wavelength edge), grows progressively larger for increasing input power. The generated SC for the highest input energy of 134pJ is observed to extend from 1 µm to above 1750 nm (OSA limitation) and is computed to reach 2 µm, which gives a 1000-nm SC bandwidth.

8073B-102, Session 10

Nonlinear effects generation in suspended core chalcogenide fibre

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In recent years much work has been devoted to non silica microstructured fibres with different designs and various elaboration processes. Their background losses were typically of several dB/m. In the case of chalcogenide glasses, the interest is to combine the uniques properties of these glasses (large infrared transparancy, high refractive index and non linear coefficients) to the ones of microstructured fibers which allow dispersion management and small effective areas.

In this work we report our achievements in the elaboration and optical characterizations of low-losses suspended core optical fibers elaborated from As2S3 glass. For preforms elaboration, alternatively to other processes like the stack and draw or extrusion, we use a process based on mechanical drilling. The drawing of these drilled preforms into fibers allows reaching a suspended core geometry, in which a ≈ 2 µm diameter core is linked to the fiber clad region by three supporting struts. The different fibers that have been drawn show losses around 0.5 dB/m at 1.55 µm. The suspended core waveguide geometry has also an efficient influence on the chromatic dispersion and allows its management. Indeed, the zero dispersion wavelength, which is around 5 µm in the bulk glass, is calculated to be shifted towards around 2 µm in our suspended core fibers. For comparison with dispersion numerical simulations, we have measured the dispersion properties of our fibers between 1.2 µm and 1.7 µm with the help of a home-made interferometric setup. A very good agreement is obtained between the theoretical and the experimental values.

In order to qualify their non linearity we have pumped them at 1.995 µm with the help of a fibered ns source. This source is a home-made ns mode-locked laser from ONERA. At this pump wavelength, the fibre exhibit a quite low dispersion (between -100 ps/nm.km and 0 ps/nm.km) but we are still in normal dispersion regime. We worked on 10 meters of a 2.5 µm suspended core chalcogenide fiber.

We have observed a strong nonlinear response with evidence of spontaneaous Raman scattering and strong spectral broadening. For an injected input peak power of 6W we observe one spontaneous Raman stoke emission, localized around 2.15 µm. For injected input peak powers larger than 19W we observe the second stoke emission around 2.35 µm. Based on simulations, the first Raman peak could be localized in the anomalous dispersion area of the fiber. At least it is very close to its zero dispersion wavelength. Moreover, the graph aspect allows to consider that hypothesis. Indeed, we also observe a strong spectral broadening from ≈ 2 µm up to above 2.4 µm.

8073B-103, Session 10

Tellurite suspended nanowire surrounded with large holes for single-mode SC and THG generations

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Nanowire waveguides have attracted much attention in recent years because of their impressive applications in microscale and nanoscale photonic devices. Compared with the naked nanowire, suspended nanowire has the advantages such as tailorable dispersion, high strength, with protective tube shaped cladding and high fabrication efficiency. For a suspended nanowire, the holes surrounding the core are expected to be as large as possible to propagate the light at wavelengths as long as possible. Additionally, a large holey region is significant for its applications in sensors. However, the fabrication of nanowire surrounded with large holes is still a challenge so far. In this paper, a method which involves pumping positive pressure of inert gas in both the cane fabrication and fiber-drawing processes, is proposed. By using the inflation pressure of nitrogen gas, a cane with the core diameter of 50 µm and hole diameter of around 500 µm is fabricated. The thickness of the long struts is only around 10 µm. Such a delicate cane is difficult to be realized by other method. By using this cane under further inflation of nitrogen gas, A suspended nanowire, with a core diameter of 480 nm and an unprecedented large diameter ratio of holey region to core (DRHC) of at least 62, is fabricated in the length of several hundred meters.

The chromatic dispersion and confinement loss of the suspended nanowire are calculated by the fully vectorial finite difference method. It has two zero dispersion wavelengths in the near-IR range. One is 790 nm, which is close to wavelength of 800 nm pump laser, and the other is 1190 nm, which is close to the wavelength of 1064 nm pump laser. Owing to the large holes, the confinement loss is insignificant when the wavelength of light propagated in it is 1700 nm. The propagation loss at 1557 nm, measured by cut-back method, is 8±2 dB/m. The predominant loss is most likely due to the roughness of inner surface of the nanofiber. The tube-shaped glass cladding of the suspended nanowire shifts the single-mode cutoff wavelength to 810 nm, which is much shorter than the cutoff wavelength, 1070 nm, of a naked nanowire with the same diameter.

At the pump wavelength of 1064 nm the nanowire has an optimized nonlinear coefficient. A single-mode supercontinuum (SC) generation covering a wavelength range of 900-1600 nm is obtained under the 1064 nm pump pulse with the peak power as low as 24 W. Note that for a naked nanowire with the same diameter which is the optimized size for the nonlinear coefficient of 1064 nm, it is difficult to obtain SC generation which is single mode for all wavelengths of the SC spectrum. Additionally, a single-mode third harmonic generation (THG) is observed by this nanowire under the pump of a 1557 nm femtosecond fiber laser. This work indicates that the suspended nanowire with large holes can provide high nonlinearity together with single-mode propagation, which leads to interesting applications in compact nonlinear devices.

8073B-104, Session 11

Homogenous metallic nanoparticle monolayers inside a microstructured optical fiber

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Microstructured optical fibers (MOFs) represent a promising platform technology for new biosensing devices. Using MOFs with adapted cavity diameters of about 20 to 30 µm, they can be used to carry the biofluids of analytical interest. Such cavities with their walls coated by transducer material form in combination with adequate microfluidic chips a platform for fully integrated next generation plasmonic devices. This paper describes the use of a dynamic chemical nanoparticle layer deposition (NLD) technique to demonstrate the wet chemical deposition of gold and silver nanoparticles (NP) within MOFs with longitudinal, homogenously-distributed particle densities. The plasmonic structures were realized on the internal capillary walls of a three-hole suspended core fiber. Electron micrographs, taken of the inside of the fiber holes, confirm the even distribution of the NP. With the proposed procedure fiber lengths of several meters can be coated and afterwards cut up into small pieces of desired lengths. Accordingly, this procedure is highly productive and makes the resulting MOF-based sensors potentially cost efficient. In proof-of-principle experiments with liquids of different refractive indices, the dependence of the localized surface plasmon resonance (LSPR) on the surroundings was confirmed. Comparing Raman spectra of NP coated and uncoated MOFs, each filled with crystal violet, a significant signal enhancement demonstrates the usability of such functionalized MOFs for surface-enhanced Raman spectroscopy (SERS) experiments.

8073B-105, Session 11

Fabrication of rocking filters in microstructured silica fibers using CO_2 laser

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A rocking filter is a type of long period grating, which resonantly couples orthogonally polarized fundamental modes guided in a birerfringent fiber. The coupling effect is obtained by periodic, permanent twists of the fiber around its symmetry, which can be made using fusion arc or CO2 laser. In this communicate, we will present in details the fabrication method based on CO2 laser. Impact of fabrication conditions on transmission characteristic will be discussed basing on experimental and numerical results. We will also present different examples of the rocking filters fabricated in birefringent microstructured fibers including multi resonance filters, apodized filters, -phase-shifted filters, and chirped rocking filters. Finally, we will also discuss possible sensing applications of selected rocking filters. The record high sensitivity to hydrostatic pressure, reaching 10 nm /MPa, will be demonstrated for the filter fabricated in a specially designed birefringent microstructured fiber with increased sensitivity to hydrostatic pressure.

8073B-106, Session 11

Measurement of chromatic dispersion of polarization modes in holey fibers by white-light spectral interferometric techniques

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In this paper, we present two white-light spectral interferometric techniques for measuring the chromatic dispersion of polarization modes in holey fibers with the birefringence induced by two large holes adjacent to the fiber core [1]. First technique is used for measuring the wavelength dependence of the group effective index of the one of the polarization modes supported by the fiber. The method is based on the recording of a series of the spectral interferograms in an unbalanced Mach-Zehnder interferometer with the fiber of known length placed in one of the interferometer arms and the other arm with adjustable path length [2]. We apply a five-term power series fit to the measured data and by its differentiation we obtain the chromatic dispersion over a broad wavelength range (500-1600 nm) [2]. Second technique is used for measuring the group modal birefringence in the fiber [3]. The method is based on resolving the spectral interference fringes at the output of a tandem configuration of a Michelson interferometer and the optical fiber under test only in the vicinity of so-called equalization wavelength at which the optical path difference (OPD) in the interferometer is the same as the differential group OPD in the fiber [3]. From these measurements, the chromatic dispersion of the other polarization mode supported by the fiber is retrieved [2]. We measured by these techniques the chromatic dispersion of polarization modes in different pure-silica holey fibers. We revealed the dependence of zero-dispersion wavelength on the geometry of the holey fiber.

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8073B-107, Session 11

Challenges in characterization of photonic crystal fibers

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Characterization of photonic crystal fiber (PCF) presents unique challenges, in particular when use of commercial instruments and test procedures developed for standard telecom fibers is attempted. We present experience gathered during testing of PCFs within activities of COST Action 299 “FIDES”, focusing on phenomena leading to measurement errors and some ways to mitigate them. Fibers made at IPHT Jena (Germany) and UMCS Lublin (Poland) were silica-based with 80-200 um cladding diameter and either Ge-doped or undoped core of size intended for single mode operation. PCF samples under test were coupled to test instruments by fusion splicing to intermediate lengths of telecom single mode fibers (SMF), most often Corning SMF-28 or equivalents.

Work with short (0.5-100 m) and lossy (30-8000 dB/km) fiber samples, often with distortions influenced selection of test methods, especially for measuring loss and attenuation. A typical optical time domain reflectometer (OTDR) was the best instrument for measuring PCF attenuation as most samples produced strong backscattering signal even with short pulse duration. OTDR was unaffected by coupling loss variations making cutback and insertion loss methods inaccurate. Commercial OTDRs intended for testing telecom networks and LANs are unfortunately available only for few fixed wavelengths, like 1310 nm and 1550 nm in Tektronix TFP2 instrument used at NIT.

Loss of SMF-PCF splice was often considerably wavelength-dependent due to changing ratio of mode field diameters in both fibers, affecting broadband spectral loss measurements (1200-1700 nm).

Quality of SMF-PCF splices was critical. In particular, excitation of holey structure modes in PCF produced detectable apparent direction-dependent loss in SMF-PCF splice (0.2 dB and more), and severe interference seen as “noise” during measurements of polarization parameters like PMD or PDL. In such case, results of measurements of PDL with typical analyzer using JME method (Adaptif Photonics A2000) were usually useless, while PMD could be established with reasonable accuracy. Multimode propagation and vibration-induced interference effectively could preclude testing of fine dependence of fiber PMD on temperature or strain, causing random variations of test data comparable to actual changes of this parameter. This did not necessarily prevent basic fiber testing.

Results of round-robin arranged within COST-299 including PMD and birefringence measurements of two PCFs using different methods gave predominantly comparable results, with 13% and 19% p-p differences; no measurement method was clearly superior. However, few odd results shown gross errors attributed to excitation of strong higher order modes in fibers under test.

Short review of peculiarities in PCF handling and cleaving is also included, especially with respect to infiltration by solvents and enface contamination.

Temperature testing of liquid-infiltrated PCF could be time-consuming due to slow settling of fiber parameters following change in temperature - up to 40 minutes.

Fusion splices protected with heat-shrinkable sleeves were used successfully to apply twist or tensile strain to several PCF samples. Fibers were fragile, breaking at strain below 2%. Twisted PCF sometimes failed in unusual way - a spiral break of cladding did not extend through the holey structure.

8073B-108, Session 12

Analytical studies of modulation instability and nonlinear compression dynamics in optical fiber propagation

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Developments in photonic crystal and other classes of novel optical fiber are leading to an increasing number of high quality experimental studies that are pushing the theoretical descriptions of propagation in nonlinear guided wave structures. Motivated by continuing studies into the physics and applications of supercontinuum generation, much recent work has been focusing on the initial noise-driven spectral broadening dynamics, and we describe here the results of our own studies of spectral broadening described by analytic breather solutions of the nonlinear Schrödinger equation. These solutions have previously allowed us to predict spectral properties that are in excellent agreement with experiment and we now extend this work to consider an approximate form of the analytic solution can be derived for sufficiently large distances. This allows us to optimize initial conditions aiming to generate ultrashort pulse trains from weakly-modulated initial fields. These results are examples of only a very small number of analytic descriptions of optical field propagation in highly nonlinear fiber.

8073B-109, Session 12

Electromagnetic analysis and characterization of photonic crystal fibers with slit-like geometry

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We propose a rigorous electromagnetic analysis for a Photonic Crystal Fiber (PCF) geometry consisting of multiple slits that go across the fiber core. The slits are regarded as invariant along the transverse dimension x, but they can exhibit variable widths along the longitudinal dimension z as well as multiple bends that allow to change their orientation in the yz plane. In order to analyze and characterize the electromagnetic behavior of the considered geometry, we use the Finite-Difference Time-Domain (FDTD) method assuming different refractive indexes for the fiber slits, cores and claddings. The first step of our FDTD analysis is the simulation of ultrashort pulse propagation along the PCFs, which allows to study the pulse shaping, pulse delay and spatiotemporal dispersion as a function of the slit width profile along the axis z as well as the multiple bends in each PCF. In a second step, the frequency-domain analysis of the results obtained for ultrashort pulses allows to characterize the PCF structure in terms of polarization and birefringence, which are computed by assuming a linearly polarized input beam with a polarization angle of 45 degrees respect to the axis x. Once a single fiber is characterized, our analysis focuses on the combination of multiple PCFs with slit-like geometry. In particular, we apply the FDTD method to analyze bending effects as well as evanescent coupling between different fibers. Besides, we will consider the possibility of using coupling elements with slit-like geometry between different guides. In the final part of our work we focus on the pulse shaping analysis for different input ultrashort pulses with (spatial) Gaussian profiles. In such analysis we study the influence of the Gaussian beam divergence on the pulse propagation through the considered PCF by varying the spatial width of the pulses.

8073B-110, Session 12

Photonic crystal fiber with flattened dispersion

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The contribution of this work is a new flat-dispersion fiber operating at telecom wavelengths. The investigation of chromatic dispersion in PCFs is implemented by the study of modified highly-nonlinear PCF with flattened dispersion. Required dispersion properties, achieved by balancing material and waveguide dispersion contribution, should be done wide spectrum of wavelengths. Microstructured optical fiber confining light in a small doped core can have two zero-dispersion points, which can be tuned by adjusting the fiber geometry, resulting thus in wide parabolic diagram. Since specific conditions are met, nearly flat zero dispersion over telecom spectrum can be produced. Flat dispersion could be used for dispersion compensation purposes in systems with wavelength division multiplex. Possibilities of obtaining anomalous or zero dispersion in photonic crystal fibers are concerned. The main attention is paid to photonic crystal fibers that exhibit unique properties, being the result of selective doping of rings of holes in considered structures by using water. It is shown from numerical results that flattened dispersion of - 0.025 ps/nm/km from a wavelength of 1200 nm to 1700 nm is achieved using a highly nonlinear photonic crystal fiber. The proposed structure parameters are, as follows: a high index material is used (GeO2) with refractive index 1.48 and only three air rings at the cladding are present. The doped core radius is: 7.4 µm which is relatively big comparing to all above studied structures. The presented systematic study includes the description of mutual relations between fiber chromatic dispersion and the structural or material parameters. The above knowledge is used to optimize the structure to achieve ultra-flattened chromatic dispersion. The results are obtained by using the full-vectorial finite difference frequency domain method. As far as fabrication interests are concerned, a special attention should be taken during the fabrication of the core since the results are highly sensitive to the core radius dimension. The core is greater than doping region, which is hard to fabricate in practice, however this configuration is found to be optimal from the numerical analysis. Last but not least, the hole diameter imprecision during fiber drawing process can have significant influence on the dispersion slope. That is expected, since hole diameter imprecision damage the balance between waveguide and material dispersion. Utilizing all the previous results provides a well-defined procedure to design ultra-flattened and ultra-low chromatic dispersion profile, the future study will focus on achieving flattened anomalous dispersion to be better implemented for telecommunication applications.

8073B-111, Session 12

Dispersion design of all-normal dispersive microstructured optical fibers for coherent supercontinuum generation

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Recently, the generation of coherent, octave-spanning, and recompressable supercontinuum (SC) light has been demonstrated in optical fibers with all-normal group velocity dispersion (GVD) behavior by femtosecond pumping. In the normal dispersion regime, soliton dynamics are suppressed and the SC generation process is mainly due to self-phase modulation and optical wave breaking. This makes such white light sources suitable for time-resolved applications.

The broadest spectra can be obtained when the pump wavelength equals the wavelength of maximum all-normal GVD. Therefore each available pump wavelength requires a specifically designed optical fiber with suitable GVD to unfold its full power.

We investigate the possibilities to shift the all-normal maximum dispersion wavelength in microstructured optical fibers from the near infra red (NIR) to the ultra violet (UV). In general, a submicron guiding fiber core surrounded by a holey region is required to overcome the anomalous material dispersion of silica.

Photonic crystal fibers (PCFs) with a hexagonal array of holes as well as suspended core fibers are simulated for this purpose over a wide field of parameters. The PCFs are varied concerning their air hole diameter and pitch and the suspended core fibers are varied concerning the number of supporting bridges and the bridge width.

We show that these two fiber types complement each other well in their possible wavelength regions for all-normal GVD. While the PCFs are suitable for obtaining a maximum all-normal GVD in the NIR, suspended core fibers are applicable in the visible wavelength range.

8073B-112, Session 12

Full modal analysis of the stimulated Brillouin scattering in As2Se3-based chalcogenide photonic crystal fiber

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The recent development of highly nonlinear photonic crystal fibers (PCF) has opened new horizons to many 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 chalcogenide PCF, is useful to amplify optical signals propagating in the backward direction of the pump. Chalcogenide-based fibers have drawn much interest because of their capacity of increasing the SBS gain. In this paper, we report on full modal analysis of the SBS in an As2Se3-based chalcogenide PCF based on the contribution of higher order acoustic modes which are sometimes ignored because of computational issues in particular on optical fibers that act as acoustic antiwaveguides. To the best of our knowledge this is the first report of SBS in a PCF made of As2Se3 chalcogenide glass.

Our study is performed in both real and ideal As2Se3-based PCF structures and compared to silica PCF. A Brillouin gain coefficient gB of 5.59 10-9 mW-1 at =1.55 µm is found around the acoustic frequency of 8.1 GHz in the real structure which is about 698 and 609 times, respectively, higher than a fused silica fiber and a PCF silica in which we have also characterized the SBS. As a result, the Brillouin threshold Pth in the real As2Se3-based chalcogenide PCF is evaluated to be 35.98 mW for only 1-m length compared to hundreds of milliwatts found in the long silica PCF. Consequently, very low Brillouin threshold powers were found to be sufficient to generate backscattered Brillouin-Stokes component in short As2Se3 PCF lengths compared to high power levels needed to generate the Brillouin-Stokes component in the silica PCF.

8073B-113, Session 13

Sensing and actuating photonic devices in magnetofluidic, microstructured optical fibre Bragg gratings

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We have recently introduced a new approach in the utilisation and actuation of liquid matrices inside microstructured optical fibres, by infiltrating in their capillaries magnetically active fluids, namely, ferrofluids. The spatial and/or functional manipulation and optical interrogation of ferroliquids that have been infiltrated inside the capillary of microstructured optical fibres constitutes a significant Optofluidic challenge. The infiltration and manipulation of a highly viscous, non-transparent magnetic liquid inside a microstructured optical fibre, as well as, its interaction with the guiding mode, can lead to the observation of unique optical and material effects and interrogation capabilities. Bragg grating reflectors inscribed in the microstructured optical fibres are used for interrogating the sensing and actuating operations of these infiltrated ferrofluids. An update on this specific topic will be presented, focusing on the demonstration of simple magnetofluidic devices such as "on-off" Bragg grating trimmers, "in-fiber" magnetometers, ferrofluidic defected Bragg reflectors and external magnetic field modulators. The design principles of such "in-fibre" magnetofluidic photonic devices will be analysed, along with their particular functionalities and

application prospects. In addition, the infiltration and fibre capillary functionalisation processes will be presented, and the effect of the ferrofluidic section on the guiding and scattering properties of the microstructured optical fiber Bragg gratings will be discussed.

8073B-114, Session 13

Photonic crystal based ultra-broadband transmission system for wave-band division multiplexing

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In this report, a photonic crystal fiber based ultra-broadband transmission system is proposed and experimentally demonstrated. The conventional optical fibers have been ultimately developed in terms of transmission loss and broadband characteristics. More than tens of Tra-bit/s optical data transmissions have been reported. However, because the conventional optical fiber tends to have multi-mode characteristics in the lower wavelength range, it is not suitable for communication application in typically less than 1.2-um wavelength range.

To meet with a continued demand for expansion of transmission capacity, a new optical frequency resources available for optical communications should be exploited. Because a photonic crystal fiber has unique features such as endlessly single mode characteristics, 1-um waveband optical data transmission is tested as a first step using a photonic crystal fiber.

Finally, a photonic crystal fiber based ultra-broadband photonic transport system for expanding the usable bandwidth of the optical frequency resources is experimentally demonstrated. Simultaneous 3x10-Gbps transmission in the 1-um, 1.5-um and 1.6-um wavebands were successfully demonstrated over a 5.4-km photonic crystal fiber based transmission line. Clear eye-openings are observed and error-free transmissions were also successfully achieved in the three wave-bands. To construct future photonic network system, the demonstrated ultra-broadband photonic transport system using a photonic crystal fiber will be a breakthrough in pioneering the new optical frequency resources for communication application.

8073B-115, Session 13

Dispersion optimization of photonic crystal fiber long-period gratings for a high-sensitivity refractive index sensing

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Photonic crystal fiber long-period gratings (PCF-LPGs) operating near the phase-matching turning point to achieve high sensitivity to the refractive index of gas and liquid analytes infiltrated into cladding air holes are designed by numerical optimization. The vectorial finite element method is employed for the modal analysis of an index-guiding PCF and the calculation of the phase matching curves. The geometrical parameters of PCF (pitch and diameter of air holes arranged in a periodic triangular array) are optimized by using the down-hill simplex technique to engineer the dispersion of modes coupled by a LPG to obtain the turning point in the phase-matching curve at a desired wavelength for a given analyte refractive index. The resonant wavelength is subsequently extremely sensitive to the analyte refractive index, however, its large shifts can be detected with a substantially reduced resolution because the resonance dip in the LPG transmission spectrum is very broad. On the other hand, the broad resonance provides a broadband operation of a PCF-LPG sensor and its high sensitivity to the refractive index can still be achieved by relying on changes in the coupling strength (and consequently in the transmission loss) rather than in the resonant wavelength of LPG. We consider coupling between the fundamental core mode and the first-order symmetric cladding mode. We also explore an alternative approach based on coupling between the fundamental core mode and the fundamental space-filling mode instead of the individual cladding mode. The PCF-LPG structures optimized for refractive-index sensing are also assessed for label-free biosensing.

8073B-116, Session 13

Polymer PCF grating sensors based on poly(methyl methacrylate) and TOPAS cyclic olefin copolymer

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Fibre Bragg grating (FBG) sensors have been fabricated in polymer photonic crystal fibre (PCF). Results are presented using two different types of polymer optical fibre (POF); first multimode PCF with a core diameter of 50µm based on poly(methyl methacrylate) (PMMA) and second, endlessly single mode PCF with a core diameter of 6µm based on TOPAS cyclic olefin copolymer. Bragg grating inscription was achieved using a continuous wave 325nm helium cadmium (HeCd) laser focussed through a phase mask. Bragg gratings have been manufactured in both the 1550nm and 800nm spectral regions. Both TOPAS and PMMA suffer from a high attenuation of around 1dB/cm in the 1550nm spectral region, resulting in fibre lengths being limited to no longer than 10cm. However, both have a much improved attenuation of under 10dB/m in the 800nm spectral region, thus allowing for the device length to be in the region of 20cm. The focus of current research is to utilise the increased length of POF, widening the range of application of such sensors. The Bragg wavelength shift of a grating inscribed in the PMMA fibre at 827nm has been monitored whilst the POF is thermally annealed at 80°C for 7 hours. The large length of POF enables real time monitoring of the grating, which demonstrates a permanent negative Bragg wavelength shift of 24nm during the 7 hours. This annealing process has allowed the Bragg wavelength to be tuned to a particular light source by varying the length of time the POF is thermally annealed for. Additionally inducing a permanent Bragg wavelength shift has created the possibility to manufacture multiplexed Bragg sensors in POF using a single phase mask in the UV inscription manufacturing.

In addition, exploiting longer lengths of TOPAS POF for the manufacture of FBGs in the 800nm region will allow some of the advantages of TOPAS to be exploited. TOPAS has a much lower affinity for water than PMMA, for example. This should allow for the elimination of cross-sensitivity to humidity when monitoring temperature changes or axial strain, which is a significant concern when using PMMA based FBGs.

8073B-117, Poster Session

Tellurite composite microstructured optical fibers with high nonlinearity and flattened dispersion for nonlinear application

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Four-wave mixing (FWM) is one of the basic nonlinear optical phenomena observed in optical fibers and leads to many applications such as parametric amplification, wavelength conversion, and oscillators. A low group velocity dispersion with a low dispersion slope is necessary to achieve a broadband and highly efficient FWM process. As microstructured optical fibers (MOFs) possess a flexibility to engineer the chromatic dispersion properties, they are very promising for optical parametric amplification. Some silica MOF designs with ultraflat dispersion have been reported, but the nonlinear coefficients of these MOFs are often less than 0.05 m-1W-1. Recently, more attention has been paid to non-silica glasses with high nonlinearity, such as tellurite and chalcogenide glasses. Tellurite glasses have better chemical and thermal stability compared to chalcogenide glasses. They are attractive for the nonlinear applications. In this paper, we propose a tellurite core phosphate cladding composite MOF with high nonlinearity and flattened dispersion for nonlinear application.

The refractive index difference between tellurite core and phosphate cladding is as high as 0.4, this high index difference between the core and the cladding enables a large waveguide dispersion contribution and hence flattened profiles even at wavelengths where the material dispersion is very large. As the thermal properties of the core tellurite glass match with those of the cladding phosphate glass, the fabrication of the proposed MOF becomes feasible. Using highly nonlinear MOF, the nonlinear effects including four-wave mixing can be realized efficiently. We propose the MOF structure with the hexagonal identical air hole introduced in phosphate cladding surrounding a tellurite core. It is obvious that by proper choice of the fiber design and, it is possible to obtain a high nonlinear coefficient simultaneously with the flattened dispersion. The significant FWM can occur at relatively low peak powers and over short propagation distances, and such processes are possible to take place in much greater frequency range. A full vector finite element method (FEM) with the perfectly matched layer (PML) boundary condition is utilized to analyze the dispersion and nonlinear coefficient. To realize flattened dispersion, the structure parameters are optimized such as the tellurite core diameter, the air hole diameter and the distance between the centers of the two neighboring air holes (pitch). The ultraflat dispersion curve is obtained for tellurite core of 1.1μm, pitch of 1.1 μm and air hole diameter of 0.5 μm. In this case, the flattened dispersion with value between -4 and 0.05 ps/nm/km is obtained ranging from 1400 to 1600 nm. The nonlinear coefficient is as high as 2.5 m-1W-1 at 1.5 μm. We present the simulated results of the optical parametric amplification in the proposed MOF. The optical parametric gain is calculated for different fiber lengths and peak powers. The optical parametric gain bandwidth of nearly 200 nm can be achieved in composite tellurite/phosphate MOF with the length of 2.5 m and the pump power of 0.4 W.

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8074-01, Session 1

Advances in digital holographic microscopy: coherence-controlled microscope

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The paper deals with the principles, fundamental imaging modes and devices designed for digital holographic microscopy (DHM). Possible prospects of the future development of this unique microscopic technique are suggested and demonstrated.

Quantitative phase contrast (QPC) is the basic imaging mode of DHM. Unlike the Zernike phase contrast or the Nomarski DIC, the QPC image directly represents a phase shift of an image wave. DHM is applied frequently as a living cells observation tool providing a strong imaging contrast by a completely non-invasive method. Moreover QPC images can be straightforwardly interpreted as the signal proportional to the density distribution of cell dry-mass. Living cells shapes, positions, and their time evolution can be derived by digital processing of the QPC record. Digital image focusing can be accomplished using a single hologram record and cells can be thus traced in 3D by processing of holographic time-lapse series.

Current experimental and commercial DHMs use the off-axis holographic setup. This enables a stable record even of very fast processes to carry out. Their optical setup is based on conventional (i.e. Mach-Zehnder or Michelson) interferometers that need coherent illumination, which brings substantial disadvantages: the image quality is decreased by a coherence noise and unwanted interferences and the image resolution is worsen. Usually a compromise solves the problem by slightly decreased coherence of illumination that still provides an acceptable contrast of interference fringes but also partially reduces the coherence artefacts.

An uncompromising solution is achievable by the incoherent holography method proposed by Leith and Upatnieks (JOSA 1967). They used the so-called achromatic interferometer instead of a classic one. In this optical setup, an off-axis high-contrast hologram is formed with an arbitrary degree of the illumination coherence. In this way, the resolution and the image quality typical for a microscopy with an incoherent illumination can be achieved. Moreover, a strong reduction of the light coherence leads to the coherence-gating effect. Light scattered outside the object plane is suppressed in the final image, which makes the image similar to that of a confocal microscope.

The principle of the Leith achromatic interferometer used in the optical design of DHM extends substantially its imaging capabilities. The character of a DHM image can be controlled by the degree of illumination coherence between two extremes corresponding to a classic coherent holography with a 3D reconstruction possible and confocal-microscopy-like imaging.

The above described control of imaging characteristics by the illumination coherence was proved experimentally by the coherence-controlled holographic microscope (CCHM), which is DHM based on the achromatic interferometer. QPC provided by CCHM is a promising instrument of future evaluation of a living cancer cells behaviour, particularly, from the point of view of intracellular motility. The presence of the coherence gate is demonstrated by imaging of model samples and cells through scattering obstacles and inside opalescent media.

8074-02, Session 1

Single particle atmospheric aerosol analysis using digital holographic microscopy

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The aim of this work was to calculate the refractive index of transparent atmospheric aerosols, which have biological origin, using a holographic method. The samples were collected on filters, using a miniature impactors for particles with dimensions smaller than 10µm (on even one axis), from a peripheral urban area, at a height of over 20 meters. Their chemical and physical properties, influence directly and indirectly the climate behavior. Due to their organic or inorganic origin, each atmospheric aerosol particle has different size, shape and optical properties which have a determinant role in LIDAR measurements. An important parameter to calculate the backscatter cross section and optical depth profile is the refractive index of the atmospheric aerosol particles.

In our laboratory study, their sizes along the propagation axis and refractive indices, introduce phase shifts which are recorded using digital holographic microscopy (DHM) technique. The samples, which contain transparent and opaque particles on a glass slide, are placed inside the experimental setup, based on the Mach-Zehnder interferometer. Two microscope objectives are introduced in reference and object arm to ensure the same curvature of the wavefront. Using DHM technique, we recorded on a CCD camera (Kodak sensor of Pike F-421B type, 2048×2048pixels, 7.4µm pitch) hundreds of holograms which contain the diffraction pattern from every aerosol particle superposed with the reference wave. We reconstruct the map of the phase shift introduced by the sample, using an algorithm based on the Fresnel approximation, where every aerosol particle is visualized separately. This technique has a nanometric resolution along the propagation axis, but in transversal plane, is restricted by the diffraction limit. Digitally, we scan the entire volume with nanometric resolution and reconstruct different depths from one single hologram recorded in the experimental setup (without mechanical movements). The calibration was done using an object with known dimensions fabricated using e-beam lithography. To decouple the information about thickness and refractive index from the phase shift maps reconstructed in DHM, we employed some complementary measurements done in confocal microscopy (only for thickness).

This study was done with the aim to establish the distribution of the bio-aerosols in the total atmospheric aerosol composition after dimensions, shapes, projections, profiles and refractive indices (real part at 632.8nm), for a summer week (July 2010), in Magurele, a rural location near the urban and industrial agglomeration of capital city, Bucharest. Our analysis separates four main classes of atmospheric aerosols particles (wires, columns, spherical fragments, and irregular) and establishes that the predominant class is the first one. For wires, which have biological origin, the refractive index was calculated starting from the phase shift introduced by them in the optical path and modeling for their cylindrical shape. DHM permits not only the particles visualization, but also gives the basic information useful to determine some physical properties of the sample, such as refractive index, dimensions, profile, projection. In the case of our samples it is clear that only when laboratory and field measurements are effectively bridged, we can fully understand the properties of the atmospheric aerosols particles.

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8074-03, Session 1

Statistical analysis of the influence of noise in digital holography

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Digital holographic microscopy (DHM) is a non-invasive technique for imaging transparent samples like cells and tissue. It has unique advantages like complete aberration compensation, shape measurement and high axial resolution with sub-wavelength accuracy. The phase of the reconstructed image is important in digital holographic microscopy. For quantitative phase contrast microscopy of transparent samples, much of the object information is in the phase variations of the transmitted or reflected light. Digital holographic methods have been shown to give a sub-wavelength axial resolution and this axial variation over the surface of the sample is dependent on the accuracy of the phase retrieval. We study the influence of the common noise sources like shot noise, quantization noise and speckle from a statistical point of view and show how this noise limits the accuracy of surface profile measurement. We also present techniques to suppress the influence of these noise sources and improve accuracy of the phase retrieval.

8074-04, Session 2

Digital holography for microscopic imaging and 3D shape measurement

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Digital holography is used for a wide range of applications. A lot of techniques deal with holographic microscopy or the 3D shape measurement of objects. We present our approaches to these applications.

To increase the resolution of a microscopic imaging system a method for aperture synthesis is applied, where the spatial frequency shift, the global phase differences and the amplitude ratios of the individual sections of the Fourier spectrum are measured by using an overlap between them. It is shown that this method can be performed out with pixel and sub-pixel accuracy. The experimental holographic setup uses tilted illumination beams realized by an LCoS SLM, which can be easily adapted to the numerical aperture of the microscope objective.

For the 3D shape measurement of arbitrary diffuse-reflecting macroscopic objects a novel approach is demonstrated, which uses common digital holographic setup together with a second CCD and an LCoS to modulate the object wave. Our idea is to capture a series of holograms from multiple positions and to apply concepts of structured light photogrammetry, which deliver more accurate depth information. The method yields a dense 3D point cloud of a scene.

8074-05, Session 2

Computer generated hologram for 3-D display from ray information on tilted surface

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Holography is the technology to reconstruct ideal 3-D objects in space. Then, even though it needs huge data and spends long computational time, it has long been attracting great deal of attention to be used for 3-D display. In this sort of 3-D display, CGH technology that generates hologram by calculation is expected to reconstruct realistic or artistic 3-D objects. There are many studies for this purpose, but, it is hard to reconstruct such objects even now. It would be the reason that most studies use simple model such as aggregate of point light sources historically in order not to spend vast amount of time for hologram generation.n

As taking account of rapid computer development, we will easily generate hologram even if 3-D objects are presented by complex model in near future. With this expectation, some studies have been started to develop CGH methods using complex model to reconstruct more realistic or artistic 3-D objects for holographic 3-D display. One of the feasible methods in these studies is the combination of CG technology and wave propagation theory [1]. This method describes 3-D objects by CG data, illuminates them with some light sources, and generates ray information around 3-D objects using rendering method in CG technology. After that, it generates both wavefield and hologram using not only the rendered ray information but also wave propagation theory. In this time, an issue is how to calculate wavefield actually, which influences the quality of 3-D objects reconstruction. In this paper, we introduce our approach for this issue.n

The assumptions of our approach are as follows. The 3-D objects are described by popular CG format that treats aggregate of surfaces at least, and ray information on the surfaces can be calculated by CG technology. Hologram plane is flat. Each surface of 3-D objects has its normal vector, i.e., it is tilted and does not parallel to hologram. All data, such as ray information and wavefield, are discrete. Under these assumptions, what we totally developed was how to transform the discrete ray information into discrete wavefield on tilted surface, how to decide the sampling pitch on tilted surface, and how to propagate the light from the tilted surface to hologram plane.n

In our approach, we transform the ray information into wavefield in consideration of both tilted angle of the surface and the ray direction toward hologram plane. The ray direction we treat on tilted surface is what we want to reconstruct at hologram plane. Wave propagation is general method, such as Fresnel transform or Rayleigh-Sommerfeld diffraction integral. According to our approach, even though surfaces are tilted, the sampling pitch of them can be defined, which is an advantage of our approach.n

[1] K. Wakunami, M. Yamaguch, “Calculation of computer-generated hologram for 3D display using light-ray sampling plane,” SPIE Practical Holography vol. 7619 (January 2010).

8074-07, Session 2

Optical reconstruction of three-dimentional object from digital holograms using phase information calculated by continuous wavelet transform

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We propose to record digital Fourier hologram of a 3D diffuse object and to reconstruct numerically and optically by using phase-only information. This phase-only information is obtained by continuous wavelet transform (CWT) from the intensity of digital Fourier Hologram. 3D object image is obtained by numerical reconstruction on computer and optical reconstruction by using a phase-only liquid crystal spatial light modulator (SLM). Numerical and experimental results are presented.

8074-08, Session 3

Modelling of a spatially-frequency spectrum of security holograms and laser analyzer for their identification in real time

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The urgency of application of the laser analyzer for identification in real time of security holograms for paper and plastic documents is shown.

The essence of a method consists in reception of a spatially-frequency spectrum (SFS) analyzed of microstructure security holograms (SH), description SFS-SH by means of integral, dotty and combined characteristics. Then identification analyzed SH by a correlation method of the identification by comparison of characteristics SFS analyzed SH with characteristics reference SH is made. For this purpose it is enough to shine SH laser (or light-emitting diode) radiation to construct by means of Fourier -objective SFS-SH to register its matrix receiver of radiation and to process a signal by means of algorithms in the electronic block.

The mathematical model of a spatially-frequency spectrum of the SH is offered, constructed and investigated. We will consider SFS-SH in the limited sector of spatial frequencies U ij and corners W ij. Then

SFS-SH it is possible to describe by means of a number of integrated parameters: integrated frequency parameter, integrated angular parameter, sector integrated parameter, average frequency and an average corner, average frequency and an average corner on the given frequency.

Sector integrated parameter Di, j is equal to size normalized integral from a capacity spectrum on sector of a frequency semiplane and displays quantity of energy SFS-SH in square sector. Integrated frequency parameter Ju and integrated angular parameter Jw are similarly defined. Thus, SFS any SH can be characterized a file of sector integrated parameters D {Dij} and average corner Waver.

Usually in SFS-SH there is limited enough number of spatial frequencies U ij. Then SFS-SH it is possible to describe also by means of the selective list of co-ordinates of the spectral peaks named in dot parameters. Process of the given description consists in search of peaked peaks in a spectrum, definition of their co-ordinates (U ij; W ij) and drawing up of the list of the given coordinates. The algorithm which basic stages :1 has been developed for definition of peaks in SFS-SH) the exception is low - also high-frequency parts SFS-SH from a zone of search of peaks; 2) a threshold filtration of noise; 3) calculation of a derivative for each point SFS-SH from a zone of search of peaks; 4) definition is or is not each point in SFS-SH a point of a local maximum on behaviour of a derivative in a vicinity of this point; 5) whether definition are the found local maxima peaked peaks.

Computer modelling of process of identification SH taking into account presence of noise is spent. Thus as entrance data files of the integrated sector and combined parameters reference and identified SH are used. Then their correlation analysis is made. The identifying rule consists in maximized correlation functional which should exceed the threshold level defined by criterion of detection (for example, Neumann-Pirson). Thus, the correlation method of the identification allows to make identification of protective holograms by the set criterion of detection with probability of correct detection PDet and probability of false alarm PFalse.

The optical scheme laser analyzer for identification SH is offered and experimentally investigated.

8074-09, Session 3

Synergy of diffraction and moiré principles in optical devices for document security

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Moiré can be observed by overlaying a pair of fine regular opaque grids. It is a pattern of light intensity modulation, which varies depending on the grids' mutual alignment and on shifting one grid with respect to the other. One grid, the data carrier, may contain some information, which is impossible or at least very difficult to retrieve or interpret observing the grid by naked eye. The other grid, the revealer, serves for reading the information stored in the data carrier. Slight discrepancy of grid periodicity between the data carrier and the revealer may cause some beneficial spatial shaping of the information, magnification in one or both dimensions in particular. If the grids have identical periodicity but are mutually phase-shifted within an area, a black-and-white pattern may be observed, with the effect of positive-to-negative switching on moving the revealer over the data carrier.

Moiré patterns find application in security printing, serving to detect copies of original documents, facilitating authentication of them or revealing encrypted information. Both the grids forming a moiré pattern used to be generated by means of printing techniques. However, integration of them in security holograms or other diffractive optically variable image devices (DOVIDs) has been reported by several authors or been a subject of some patents too. Design of the data carrier follows the same methodology as that used when printing techniques are employed. Diffraction from a DOVID's grating structures results in iridescent appearance and dependence on the DOVID's orientation. Moiré and diffraction are here in a combination but, despite the fact that high diffraction efficiency facilitates good visibility of moiré, each phenomenon operates independently.

The present paper attempts to demonstrate an alternative approach when moiré is visible not owing to slight local geometric differences between the data carrier and the revealer but because of local variations of grating periods in the data carrier that show up as areas of contrasting colours on superimposing the revealer. A sort of synergy between diffraction properties of gratings and principles of moiré revelation takes place here.

8074-10, Session 3

Fully synthetic holograms and DOVID

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Holography has passed quite a remarkable way since its original invention and holograms have been widely exploited in a variety of fields of applied optics and industry. Our contribution deals with the advanced e-beam originated diffractive optically variable devices (DOVIDs) used for protection of goods and documents.

Recent development in the electron beam assisted mastering of DOVIDs has led to a production of very unique synthetic diffractive devices and features offering original visual effects. We have also proceeded further with the resolution of the origination tool, now reaching its theoretical physical limits. Both, the beam shape and its relative position, can now be controlled with an increment of 10 nm. In others words, it actually represents 2,500.000 dpi resolution. Having a power of arranging each e-beam stamp independently with 10 nm differecess allows to sample the exposition data with a subdiffraction accuracy. It apparently yields quite unique eye observable feature. As an example, we can routinely introduce a variety of predefined color/spectral effects to otherwise fully achromatic features of the Nanogravure category. Further, we may produce omni-directionally observable flops and watermark-like features with specific, synthetically introduces layman observable properties. Finally, we introduce a revolutionary DOVID element based on a full synthesis of the picture, where pseudo-randomly distributed rudimentary diffractive elements are shielded in a sophisticated way. Such full synthetic security holograms can imitate a variety of known holographic features and most importantly, they enable a production of personalization of each DOVID on an unbreakable forensic and cryptographic level.

8074-11, Session 3

Sequential aberrations compensation in an off-axes holographic imaging system

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Wide-angle, and off-axis imaging systems both require, high level of geometrical aberrations corrections. In this paper we analyze, theoretically and by numerical simulation, such one wide angle, off-axis (>45°) imaging system in which fundamental component is a Bragg volume hologram (BVH) operating in catadioptric (i.e. reflective) conditions. This hologram was originally recorded in high sensitivity silver halide or dichromate gelatin (DCG), i.e., in high diffraction efficiency and low noise materials by superposition of two counter-propagating coherent laser beams. One beam was plane reference and the other divergent spherical. Plane reference beam was directed to the recording hologram plate at an angle of 50° to the normal, while the object spherical wave was centered orthogonally at one meter distance from the recording plate. Then the final BVH was obtained by contact copying into photopolymer material. The BVH was used to produce a point by point virtual image in a sequential way, by varying the angle of incidence of the reading plane wave. The inherent geometrical aberrations, dominated by comma when using this BHV in imaging setup, were supposed to be compensated (i.e. corrected) by one reconfigurable transmission Computer-Generated Holographic Optical Element (CGHOE). The CGHOE was inserted into the imaging system optical chain. The CGHOE was implemented as a two-dimensional phase distribution using electronically addressable spatial light modulator. The phase transfer function (PTF) implemented in the CGHOE depends on the position of the image point in the virtual space. The sequential approach to imaging presents the advantage as it allows for individual optimized correction of aberrations for each and every point of the image scene rather than a global and parallel (simultaneous) optimization for the entire image.

In the paper we present a method to obtain the PTF, which has to be implemented into the CGHOE to compensate for the aberrations of

the given point. Then, sequentially we implement it for all the points of the considered object field. We show that the compensation of the aberrations is theoretically possible to a considerable degree. Finally, we have experimentally verified these concepts for an object field with a finite number of twodimensional distributions of points.

8074-44, Session 3

Digital holography and phase retrieval: a theoretical comparison

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Iterative phase retrieval techniques (PRTs) represent an alternative means to digital holography (DH) for estimating the complex amplitude of an optical wavefront. Here we examine some fundamental limits of PRT systems to resolve detail in our wavefront and contrast the performance with a DH system.

8074-12, Session 4

Holographic recording diffraction gratings in BB-640 photographic emulsions with femtosecond pulses in infrared region

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The limitation of femtosecond light pulse interference can be overcome by experimental setups with diffraction orders of gratings and confocal imaging system. A modified setup with spherical mirrors, near of concentric spherical surfaces, convex an concave has been comparatively analyzed, considering pulses as short as 20 fs. With this experimental setups many holographics material can be analyzed with application at laser-induced gratings, Four-wave mixing, holographic and lithography of two and three dimensional microstructures to photonic crystal fabrication.

In this paper we show the experimental response of BB-640 photographic emulsion to the interference of two infrared femtosecond pulses. We have analyzed the influence of bleaching process and the thickness of the emulsions, considering shrinkage effects and sensitivity of photographic materials.

The experimental setup consists of an afocal system composed of two plane-convex lenses of focal length of 100 mm and numerical aperture of 0.22, with a distance between them set to be equal in order to have a 4f system. A beamsplitter is a diffraction grating that is placed at the front of focal plane of the first lens.

The gratings are recorded by the interference of two gaussian beams from a femtosecond pulse laser mode sapphire laser. The pulse width is 120 fs and 76 MHz of repetition frequency. At the interference planes the intensity is 340 mW and the area is 950 micron of diameter. In this conditions we have 0.47 MW/cm2 of pulse intensity. We have studied the intensity distribution in the superposition plane of system. The measure was made by edge-knife interferometer from Coherent Inc.

The two gaussian beam are crossing over surface, the interacting angle is 23.8 so we have a interference spatial frequency of 540 l/mm with a wavelength of 790nm. The length of overlap region between ours gaussian beams is 4600 micron depth. This regions is many times the coherence length that in our case is 36 micron so we arrive the spatial an temporal superposition of femtosecond pulse.

Due to the BB-640 photographic plate is red sensitive but with an absorption at 790 nm lower than 1%, and the grain size is 18-20nm, so the sensitivity is very low, so the exposure time need to record the gratings is from 1s to 96s. Pulse holography has been demonstrated that reciprocity law failure and we have to be considered the time have to be incremented.

We have developed the exposed emulsion by AAC an D8 developer and hipersensitized the emulsion previous to the exposure by a solution of TEA.

As a result we have experimentally demonstrated that transmission holographic gratings can be recorded in BB-640 emulsion with femtosecond laser in near infrared region with diffraction efficiency up to 30%, the thickness of the photographic emulsions and the bleached process has been analyzed and the sensitivity has been optimized with D8 developer.

8074-13, Session 4

Synthesis and properties of 1,3-dioxo-1H-inden-2(3H)-ylidene fragment and (3-(dicyanomethylene)-5,5-dimethylcyclohex-1-enyl)vinyl fragment containing derivatives of azobenzene for holographic recording materials

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In last years, there is a tendency to investigate organic glasses as holographic data storage materials. Therefore it is important to synthesize photosensitive low molecular mass organic compounds which would not crystallize and would form thin amorphous solid films.

New glassy 1,3-dioxo-1H-inden-2(3H)-ylidene fragment (1a-c) and (3-(dicyanomethylene)-5,5-dimethylcyclohex-1-enyl)vinyl fragment (2) containing push-pull type derivatives of azobenzene able to create thin layers from volatile organic solvents have been synthesized.

Compounds 1a-c and 2 are characterized with intensive absorption in UV-VIS spectrum red light region (440-640nm). They also form thin solid amorphous films from volatile organic solvents. That makes them perspective with their potential application in obtaining and researching holographic materials with 532 nm and 633 nm lasers. Thin films of synthesized glasses for researching holographic properties were prepared by spin coating technique from saturated chloroform solution and are experimentally studied at 633 and 532 nm in both transmission and reflection modes with p-p recording beam polarizations. Thin solid film sample of the compound 2 was found to be the most efficient at both wavelengths in transmission mode exhibiting the maximum self-diffraction efficiency of 9.9% at 633 nm, and 15.3% at 532 nm. The film sample of the compound 1a was the most efficient in reflection mode with the maximum self-diffraction efficiency of about 3%.

Acknowledgements

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8074-14, Session 4

Photopolymerizable thiol-ene nanocomposite materials for holographic applications

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We have recently developed a new class of holographic dry photopolymers, the so-called nanoparticle-polymer composites, in which inorganic (TiO_2, SiO_2, ZrO_2) or organic (hyperbranched polymer) nanoparticles are dispersed in monomers capable of either (radical) chain-growth or cationic ring-opening polymerization. In this photopolymer system the phase separation of monomer molecules and photo-insensitive nanoparticles takes place during holographic exposure, providing high contrast volume holograms. The inclusion of nanoparticles also yields to the suppression of polymerization shrinkage and to high thermal stability of fixed holograms, giving high dimensional and environmental stability. It was also demonstrated that the inclusion of inorganic nanoparticles could improve thermal stability of a recorded volume hologram and suppress its polymerization shrinkage as well as increasing the saturated refractive index modulation Δn and the material sensitivity S that exceed the minimum acceptable values of 0.005 and 500 cm/J, respectively, for holographic data storage applications. However, the polymerization shrinkage of nanoparticle-polymer composites was of the order of 1% that was still larger than the minimum acceptable value of 0.5%. Therefore, further shrinkage reduction is needed for their use in holographic data storage systems.

In this work we demonstrate volume holographic recording in photopolymerizble thiol-ene nanocomposite materials, the so-called holographic nanoparticle-polymer composites using thiol-ene photopolymerization, by which shrinkage can be reduced as low as 0.4%. The reduced shrinkage is comparable to other low-shrinkage dry photopolymer systems such as those including a high content of inert binder components and using monomers capable of cationic ring-opening polymerization. We investigate the photopolymerization kinetics and their relation to the observed shrinkage suppression. It is also shown that the thiol-ene based nanoparticle-polymer composites possess Δn of 0.009 and S of 1600 cm/J in the green, larger than the minimum acceptable values 0.005 and 500 cm/J, respectively. Furthermore, the improved thermal stability of holograms recorded in the nanocomposites is confirmed experimentally.

8074-15, Session 4

Theoretical and experimental analysis of chain transfer agents behaviors in photopolymer material

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The Non-local Photo-Polymerization Driven Diffusion (NPDD) model indicates how a material's performance might be improved, and provides a tool for quantitive comparison of different material compositions and to predict their fundamental limits. In order to reduce the non-locality of polymer chain growth (i.e the non-local response parameter) and to improve the spatial frequency response of a photopolymer material, we introduce the chain transfer agent (CTA). In the literature, extensive studies have been carried out on the improvements of the non-local response modifying by the CTA, sodium formate, in the polyvinyl alcohol-acrylamide (PVA/AA) material. In this article, i) based on the chemical reactions of CTA, we extended the CTA model in the literature; ii) we compare two different CTA materials, sodium formate and 1-mercapto-2-propanol with different concentrations without cross-linker in order to obtain the appropriate concentration in our material; iii) we examine the non-local responses of several spatial frequencies with the appropriate concentrations of the two CTA. Using the extended CTA model it is demonstrated that the CTA has the effect of decreasing the average length of the polyacrylamide (PA) chains formed, thus reducing the non-local response parameter, especially, in the high spatial frequency case.

8074-16, Session 4

Photo-Kinetics of Irgacure 784 sensitised photopolymer in the blue

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Holographic recording at shorter wavelengths enables the capture of holograms with greater resolution. Material sensitisation in theblue or violet may simply require a replacement of the photosensitive dye or can require the insertion of an entirely new photosensitiser system leading to completely different photoinitiation kinetics. There are several well known photoinitiator systems which have high values of the key photoinitiation process characterising parameters, e.g. molar absorption coefficient, quantum yield. Some exhibit good thermal stability over a broad range of wavelengths, i.e. from the UV to the green. An example of such photosensitiser is organometallic titanocene Irgacure 784. In this case however several key parameters are not well known and furthermore the photoinitiation kinetics have been found to vary considerably between use in the green and the blue. In this paper we study the behaviour of Irgacure 784 in an epoxy resin photopolymer when exposed using blue light. We report on our experimental results for a wide range of intensity values and present a physical model to predict the observed behaviour.

8074-17, Session 5

Recording aspects of high-resolution Bayfol® HX dry photopolymer films for holography

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We have been developing a new class of recording materials for volume holography, offering the advantages of full color recording and depth tuning without any chemical or thermal processing, combined with low shrinkage and detuning. These photopolymers are based on the two-chemistry concept in which the writing chemistry is dissolved in a preformed polymeric network. This network gives the necessary mechanical stability to the material prior to recording. In this paper we describe several aspects of holographic recording into Bayfol® HX which are beneficial for its effective use and discuss them within an elaborate reaction-diffusion model.

8074-18, Session 5

Improvement of bER using adaptive optics in angle-multiplexing holographic data storage

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Holographic data storage is expected for a large capacity and high data-transfer-rate recording system. Photopolymer materials are used in a medium, which has large multiplexing index and high stability. However, photopolymer shrinks due to photopolymerization while laser beams are irradiated. This shrinkage distorts recorded holograms and degrades the quality of the reproduced data. We have been studying adaptive optics (AO) to compensate for hologram distortion optically and improve bit-error-rate (bER) of the reproduced data. However, in angle-multiplexed holograms, it needs much time to compensate for all holograms distortions. Then we investigated reduction of compensation times and improve bERs of the reproduced data in all holograms. In our experiments, first, we recorded 60 holograms with angle multiplex, and then applied AO to the holograms before data were reproduced. In AO, the wavefront of the reference beam as input is controlled by using a deformable mirror (DM) in the path of the reference beam for reproducing, and the reconstructed beam as output is captured with an image sensor. A genetic algorithm to optimize the wavefront was used. Optimization was applied to the first and last holograms in 60 holograms. DM values between the second and 59th holograms were calculated with linear interpolation using two DM values for the first and last holograms. It does not need much time to obtain DM values between the second and 59th holograms because linear interpolation is simple calculation. When data were reproduced from 60 holograms with original wavefront, average bER of the reproduced data was 1.1 x 10-2. On the other hand, when optimized and linearly-interpolated wavefronts were used, average bER of the reproduced data were 7.8 x 10-3. However, in this case, bERs around the 30th holograms was more than 8.5 x 10-3 and these make average worse. In order to decrease bERs around the 30th holograms, one more optimization was applied to the 30th hologram. DM values between the second and 29th and between the 31st and 59th holograms were calculated with linear interpolation using two DM values for the first and 30th and for the 30th and last holograms, respectively. When three optimized wavefronts and linearly-interpolated wavefronts were used, average bER of the reproduced data decreased to 6.4 x 10-3. We found that distortions of angle-multiplexed holograms are changing linearly with number of holograms. And compensation times could be decreased from 60 to 3 times. This method is effective to reduce compensation times, which enables to improve data-transfer-rate, and improve bERs of reproduced data in angle-multiplexed holograms.

8074-19, Session 5

Experimental research of a method of multiplexing of microholograms on the thin photosensitive medium in system of holographic memory

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Abstract

The new modified holograms multiplexing method using normal to holographic re-cording medium reference beam incidence and off-normal signal beams incidence is of-fered for application in holographic memory system having high information capacity and high data rate. Signal beams are located around reference beam concentrically. In this case quantity of multiplex holograms in the same area of recording media is equal to quantity of signal beams. Experimental holographic memory system model applying offered method is tested. Possibility of multichannel optical head application for data recording and retrieving is shown. Wet photochemical processing is disadvantage of argentum halogenide recording media. Argentum halogenide “PFG-03M” produced by Slavich Company was considered for applying in holographic memory system. Photosensitive layer of “PFG-03M” is ~7-12 μm thickness.

The optical scheme of the device of record of multiplex holograms with use of a multichannel writing down head with number of channels equal to number of microholograms in the multiplex hologram is developed. The central part collimated a bunch is used as the basic bunch falling on the photosensitive environment of perpendicularly its surface. The peripheral ring part collimated a bunch is distributed by system of mirrors on channels of the multichannel writing down head, symmetrized concerning an axis of a basic bunch. For record of all file of a matrix of multiplex holograms moving a registering plate of a photographic plate on coordinates X and At by means of a two-coordinate operated table is carried out. For record of a matrix of multiplex microholograms as a photosensitive material ~7 microns have been used serially let out argentum halogenide holographic photographic plates with thickness of a photosensitive layer.

Advantages of a method:

- Absence of rotation of the registering environment and its mechanical stability, - parallel process of record (reading) of separate microholograms that provides accordingly higher speeds of record and reading of the information.

Offered method was tested on experimental holographic memory system model. Experimental holographic memory system is composed of 150 mW power He-Cd laser, 0.1 msec shutter. Expanded laser beam is directed to Fourier transform objective by plane mir-ror.

SLM is situated just after Fourier transform objective. SLM resolution is 600×800 pixels, with spatial period equals to 14 μm. SLM diagonal dimension is equal to 14 mm. Maximum SLM frame rate amounts to 60 fps. Hologram diameter is limited by diaphragm situated close to holographic recording media. Hologram diameter amounts to 0,5 mm.

During experiments on record of a matrix of multiplex holograms following parameters have been received: the size of a photographic plate - 127×127 mm; hologram books pattern includes 250×250 hologram books; single hologram book diameter will equal to 0.5 mm; single hologram book includes 20 multiplexed holograms; taking into consideration phase-coded shift multiplexing total holograms amount will equal up to 20’000’000; argentum halogenide plate (127×127 mm) data capacity will equal up to 75 Gbytes.

8074-20, Session 5

Information record in stoichiometric pure LiNbO3 single crystals

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Since the LASERS were investigated the very intensive researchers in the nonlinear optics begun. The intensive laser optics development helped to make new experiments in the nonlinear optics. The photorefractive materials attract a lot of science attention due to their very promising prospects in application. photorefractive materials could be used for new informational techniques development, for systems of optical information treatment. One of the most promising photorefractive crystals is lithium niobate (LN) crystal. LN has high nonlinear, electrooptical, photovoltaic properties, that determine the possibility of its use in holographic information record facilities.

It was believed that the information record is only possible in photovoltaic doped crystals. At this, rise of the photovoltaic dopant concentration in crystal lead to rise of record contrast range. Such record preserved up to 50 days in dark in photovoltaic doped LN single crystals.

But our work shows that the record is only possible in pure LN single crystals having stoichiometric or nearly stoichiometric composition.

Usually the recorded information erases in few minutes upon the influence of the homogeneous laser radiation. The information recorded in stoichiometric LN single crystal preserves for quite a long time - the information stayed even after one hour of homogeneous laser radiation effect. The same information record stability were observed in stoichiometric LN single crystals grown of congruous melt with addition of K2O flux.

The data on the possibility if information record in stoichiometric pure LN single crystals is obtained for the first time. We also revealed that the time of recorded information storage in much longer for the stoichiometric pure LN single crystals is obtained for the first time. We also revealed that the time of recorded information storage than for the photovoltaic doped LN single crystals.

8074-21, Session 6

Exploring unconventional capabilities of holographic tweezers

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Optical tweezers are a powerful, contactless, instruments of manipulation and analysis of micro- and nano-particles, providing valuable non-invasive diagnostic tools for several kinds of objects (colloids, cells, etc.). Although they have reached high level technological development their operation principle is still based on the intensity gradient.

Polarization holography [1] has been exploited to demonstrate how polarization gradient offers new capabilities for optical trapping and manipulation. The simplest and pure polarization pattern has been used. In the superposition region of two laser beams with orthogonal linear polarization, the intensity distribution is Gaussian while, at smaller scale, a spatially periodic modulation of the polarization state occurs. This light polarization pattern is able to simultaneously exert forces and torques in opposite directions depending on the particle’s position. It allows to perform oscillatory displacements and control the sense of rotation of several particles inside a uniformly illuminated region depending on their optical properties.[2]

Here we report an investigation of the capabilities of these holographic tweezers, exploiting liquid crystal (LC) systems. LCs represent an interesting challenge in the context of optical trapping, being characterized by anisotropy, viscoelasticity, aggregation and supramolecular configuration flexibility, richness of phenomena related to confined geometries (droplets, thin films).

Experiments with LC emulsions partially verify the expected scenario and make evidence of an unconventional trapping of spinning birefringent particles in circularly polarized fringes. This unusual trapping observed for rotating bipolar nematic droplets has suggested the involvement of the “lift force”, the hydrodynamic force responsible of the Magnus effect, originating from the peculiar optical force field.

A different holographic arrangement of optical tweezer has been also designed and tested to observe the Magnus effect when micro-sized object are trapped and manipulated by the light in a fluid.

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8074-22, Session 6

Holographic fabrication and transmittance analysis of three-dimensional photonic crystals

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Photonic crystals are microstructures in which the dielectric constant is modulated periodically. Holographic lithography is useful for making large photonic crystals easily. Especially, the method employing triple exposure of two-beam interference fringes [1] is superior. This method can create all fourteen Bravais lattices with arbitrary lattice constant. Three-dimensional photonic crystals with face-centered cubic lattice structure, whose top plane is (1,1,1) plane, were fabricated by triple exposure of two-beam interference fringes using THG of YVO4 laser with 355nm wavelength and SU-8 negative photoresist.

The transmittance of photonic crystals with face-centered cubic lattice structure fabricated by holographic lithography is analyzed by reducing the three-dimensional structure into multilayer thin films employing the effective medium theory (EMT) and matrix method [2]. The remarkable stop bands appeared at the Bragg wavelength calculated from the average of effective index. Relationships between stop bands and effective refractive index on the reduced film or filling factor of photonic atoms for a face-centered cubic lattice structure simulated by holographic lithography are shown.

The validity of EMT result is also discussed in comparison with that of plane wave expansion method for a face-centered cubic lattice structure with sphere atoms. The stop bands were calculated by using the zero-th order, the second order and higher order EMT. The stop band calculated using higher order EMT fairly well agreed with that of plane wave expansion method, while the zero-th order and the second order results roughly agreed with that.

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8074-23, Session 6

New methods of near-field holography

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At present, the possibility of surfaces characterization with subwavelength resolution by means of optical methods is very demanded, since use of radiation with shorter wavelength is not always convenient and sometimes it is even impossible. Recently it arose the optical devices (near-field scanning optical microscope and superlenses), which are capable to solve this problem. But they have a few essential disadvantages.

In the report we propose two optical methods to solve the problem of imaging with subwavelength resolution. These methods permit one to measure amplitude and phase distributions of the near-field, which contains information about subwavelength structure of the surface. This capability allows us to refer the methods to near-field holography. These methods permit one to measure near-field simultaneously all over entire surface of the sample. It provides much more rapid measurements in comparison with a near-field scanning optical microscope. Proposed methods have been tested numerically.

The first method is based on recording on photoplates of the interferograms of the near-field. A few photoplates are located over the surface under study in immediate proximity to it. Plane monochromatic spatially coherent wave is incident on the surface perpendicularly to it. This wave is scattered by the surface and the photoplates happen to be in the near-field. Thus, the photoplates record interference between field scattered by the surface and the reference plane wave. The measured interferograms are used for reconstruction of the amplitude and phase distributions of the near-field by means of solving a corresponding inverse problem. Then the surfaces characteristics (profile, distribution of refractive index etc) are reconstructed on a known near-field.

The concept of the second method consists in transformation of the near-field evanescent waves to propagating waves by means of subwavelength-structure mask located in immediate proximity to the surface (on the distance from the surface less than wavelength). Plane monochromatic wave is scattered by the surface and then interacts with the mask. The mask transfer spatial spectrum of the near-field into region of less spatial frequencies. As a result, evanescent waves, containing information about subwavelength structure of the sample, are partially transformed to propagating waves. The amplitude and phase distributions of the field, produced by the mask, are measured far from the surface by means of methods of conventional interferometry. These distributions are used as initial information for the inverse problem, intended to reconstruct amplitude and phase distributions of the near-field and subwavelength structure of the surface.

8074-24, Session 6

Estimation of quality of 3D holographic images by means of stereogrammetry

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A method for estimation quality and adequacy of reconstructed holographic 3D images by means of stereogrammetry and digital image processing is proposed. Authors will discuss several aspects and problems related with quality of reconstructed holographic images. The quality as a subjective parameter is considered and analyzed with most often-used quality criteria, which usually applied to reconstructed 3D images. Several problems that still remain open while using such criteria are reported. Much prominence will be given to adequacy of reconstruction of obtained image with the original object. Moreover, problems connected to adequacy of reconstruction moving objects will be considered, also for the case of moving observer. Several metrological characteristics (criteria) of proposed method are compared and its benefits for using in practical applications are discussed.

8074-25, Session 6

Measurement of surface resistivity/conductivity of carbon steel in 5-20ppm of TROS C-70 inhibited seawater by optical interferometry techniques

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Optical interferometry techniques were used for the first time to measure the surface resistivity/conductivity of carbon steel samples in blank seawater and in seawater with different concentrations of a corrosion inhibitor, without any physical contact. The measurement of the surface resistivity/conductivity of carbon steel samples was carried out in blank seawater and in seawater with a concentration range of 5-20ppm of TROS C-70 corrosion inhibitor, at room temperature. In this investigation, the real-time holographic interferometric was carried out to measure the thickness of anodic dissolved layer or the total thickness , Utotal , of formed oxide layer of carbon steel samples during the alternating current (AC) impedance of the samples in blank seawater and in 5-20 ppm TROS C-70 inhibited seawater, respectively. In other words, the surface resistivity/conductivity of carbon steel samples was determined simultaneously by holographic interferometry, an electromagnetic method, and by the Electrochemical Impedance (E.I) spectroscopy, an electronic method. In addition, a mathematical model was derived in order to correlate between the AC impedance (resistance) and to the surface (orthogonal) displacement of the surface of the samples in solutions. In other words, a proportionality constant (surface resistivity ( ) or surface conductivity (=1/[surface resistivity ( )] between the determined AC impedance (by EIS technique) and the orthogonal displacement (by the optical interferometry techniques) was obtained. Consequently the values and of the carbon steel samples in solutions were obtained. Also, the value of from other source were used for comparison sake with the calculated values of this investigation. This study revealed that the thickness of the anodic dissolved layer of the carbon steel sample has been removed from the surface of the sample, in the blank seawater. Therefore, the corresponding value of the resistivity to such layer remained the same as the value of the resistivity of the carbon steel sample in air, around 1x10-5 Ohms-cm. On the contrary, the measured values of the resistivity of the carbon steel samples were 1.85x107 Ohms-cm , 3.35.x107 Ohms-cm, and 1.7x107 Ohms-cm in 5ppm,10ppm, and 20ppm TROS C-70 inhibited seawater solutions, respectively. Furthermore, the determined value range of the   of the formed oxide layers, 1.7x107 Ohms-cm to 3.35.x107 Ohms-cm, is found in a reasonable agreement with the one found in literature for the Fe Oxide-hydroxides, i.e., Goethite(-FeOOH) and for the Lepidocrocite (-FeOOH), 1x109 Ohms-cm. The   value of the Goethite(-FeOOH) and of the Lepidocrocite (-FeOOH), 1x109 Ohms-cm, was found slightly higher than the   value range of the formed oxide layer of the present study. This because the former value was determined by a DC method rather than by an electromagnetic method,i.e., holographic interferometry, with applications of EIS, i.e., AC method. As a result, erroneous measurements were recorded due to the introduction of heat to Fe oxide-hydroxides. This led to higher value of the resistivity of the Goethite(-FeOOH) and for the Lepidocrocite (-FeOOH)), 1x109 Ohms-cm, compared to the determined value range of the resistivity of the formed oxide layers, 1.7x107 Ohms-cm to 3.35.x107 Ohms-cm.

8074-45, Session 6

Nonlinear light propagation in photopolymers: from self-trapped beams to 3-D optical lattices

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While liquid crystals, surfactants and colloidal crystal systems assemble into ordered phases to attain free energy minima, strikingly complex patterns can also emerge when condensed matter systems are perturbed away from equilibria. This talk will be an overview of research in our group into the dynamics of light beams that propagate while simultaneously initiating free-radical polymerisation in photopolymers. The consequent nonlinear and reciprocal interactions between the optical field and self-induced refractive index changes in the medium elicit a rich assortment of three-dimensional spatial patterns. These include self-trapping bright and dark beams, beam filamentation due to modulation instability, diffraction rings due to self-phase modulation and the formation of 2-D and 3-D bright and dark optical lattices. The potential of these optical phenomena to spontaneously inscribe complex 3-D polymer architectures that are inaccessible through conventional lithographic techniques and that would have advanced optical applications such as nonlinear photonic crystals will also be described.

8074-26, Poster Session

Preparation and characteristics of a microlens array for a digital holography application by an inkjet printing method

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In this study, microlens array for a digital holography application was fabricated by an inkjet printing method. Inkjet DOD fabrication of microlens array consisted of a basic setup utilizing a heated fluid reservoir coupled to a piezoelectric ceramic, through which a machined nozzle dispensed uniform polymer droplets to the substrate mounted to xyz microcontrollers. The spherical drops with a diameter of 33 μm were generated with a Microfab device equipped with a nozzle of 30 μm diameter. The cleaned substrate was placed on a movable xyz table, onto which the spherical drops were deposited in a dust-free atmosphere. PMMA ink was an epoxy type, which could be cured in an air-atmosphere with about 500 mW/cm2 of UV light radiation for less than 2 min and was transparent in wavelength range from 600 to 1700 nm. Due to the surface tension, the drops took a plano-convex shape rapidly and could be polymerized and hardened under UV light. Variation in not only inkjet printing condition but also surface state of PMMA substrate could be employed to modify lens shape, depth of field, and lens height. To influence the profile of microlens elements and increase the aspect ratio of hemi-elliptical lenses, we proposed the chemical modification of PMMA substrates utilized in the earlier stage of the inkjet printing, which was similar with several published studies. The physical properties of microlens array were investigated.

8074-28, Poster Session

Creation of raster relief structures on silver-halide photographic emulsions with the help of two-dimensional holographic gratings

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We have earlier considered a crossed two-dimensional holographic grating (TDHG) as an optical element that is capable of forming raster images. After recording TDHG in a light-sensitive medium with relief-phase response, it is possible to form other optical elements, e.g., microlens rasters. The principle of microlens raster formation method is as follows. After TDHG photochemical processing in a contrast developer, it represented a matrix of transparent circular holes on a nontransparent background.

The simplest method to form a microlens raster is TDHG contact-photocopying on a photographic material with a phase-relief response. However, here microlens rasters with a low filling factor are produced. In order to increase the efficiency of surface using, we proposed the following modification of the earlier-described methods. An illuminating transparency with a previously calculated light intensity distribution is placed in front of the TDHG. An image on an electron-beam type computer display was used as an illuminating transparency. By using the TDHG imaging properties as a two-dimensional camera obscura system, the distribution of the light intensity from the image on the computer display was transmitted onto a light-sensitive material (a silver-halide photographic emulsion PFG-01, Russian). After processing the photographic material by the above-mentioned techniques, a relief image of the microlens raster was formed on it with the coefficient of specimen surface filling being considerably greater as compared to that obtained previously.

Moreover, we have studied the effect of photochemical processing of photographic materials on the optical properties of the TDHG with the aim to improve these properties.

8074-29, Poster Session

Amorphous As-S-Se semiconductor thin films for holography and lithography

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Electron-beam induced changes in thin films of the amorphous chalcogenide semiconductors As-S-Se have been studied. The possibilities of practical application of this material as resists for the production of relief holograms and diffractive optical elements (DOE) are discussed. The results of two different types of etch, DOE shape and diffractive index are discussed.

8074-30, Poster Session

Analysis of the addition of a crosslinking agent in pyrromethene-HEMA based photopolymerizable holographic recording materials

S. Blaya, P. Acebal, L. Carretero, R. F. Madrigal, A. Murciano, A. Fimia, Univ. Miguel Hernández de Elche (Spain)

Since the initial works of Close et al, a great amount of research has been carried out in the field of photopolymerizable holographic recording materials. In this sense, due to the development of holographic data storage systems, a great number of compositions were developed, among them, commercial photopolymerizable systems (i.e. Aprillis and Inphase) present optimal properties such as high dynamic range, photosensitivity, dimensional stability, optical clarity and flatness etc... Among the great number of the compositions developed, one of the simplest is the three-component system based on pyrromethene dye (PM567) acting as a photoinitiator and HEMA as monomer both of them dissolved in a dry polymeric matrix of PMMA. Previously, we reported the recording of diffraction gratings in this composition, resulting in diffraction efficiencies near 60 % with exposures of 1 J/cm^2 in materials with thicknesses around 500 microns. Although, the mentioned response (best) was observed at low intensities but at higher ones lower diffraction efficiencies were reached. Furthermore, in all the studied cases inhibition periods with asymmetrical angular selectivity curves were obtained. Since, in order to solve the mentioned drawbacks, the aim of this work is to analyze the effect of the addition of a crosslinking agent (PETA) in a photopolymerizable holographic material based on a pyrromethene dye (PM567) acting as a photoinitiator and HEMA as monomer both of them dissolved in a dry polymeric matrix of PMMA. For this, diffraction gratings were recorded at different intensities and the energetic evolution of the diffraction efficiency as well as the observed inhibition period were studied as a function of the concentration of crosslinking agent. Moreover, the experimental angular selectivity curves were theoretically analyzed by the model of Kubota and Uchida, and as a result information such as the effective thickness, fringe bending and non-uniform index modulation against the thickness of grating was obtained. In general, the addition of a crosslinking agent such as PETA produces higher fringe bending with shorter inhibition period. However, it is observed that the ratio HEMA:PETA of 2:0.5 presents an optimal performance at a wide range of the analyzed intensities. In this sense, at high intensities it is obtained lower fringe bending, shorter inhibition periods and higher index modulation than the reference composition. Finally, it is important to point out that with these compositions non-ideal energetic variations of the diffraction efficiency are observed. In this work we propose that these non-ideal curves can be explained by the effects related to the recorded non-uniform gratings. For this, by introducing the energetic variation of the index modulation and the fringe bending in the theoretical treatment of Kubota and Uchida a qualitative description of the experimental energetic diffraction efficiency curves can be obtained.

8074-31, Poster Session

Analysis of the effect of the photoinitiator system composition in pyrromethene-HEMA based photopolymerizable holographic recording materials

S. Blaya, P. Acebal, L. Carretero, R. F. Madrigal, A. Murciano, A. Fimia, Univ. Miguel Hernández de Elche (Spain)

Photopolymers, due to properties such as high index modulation, real time processing and low cost, have been applied for displays, high density data storage, micro-optical elements and other information processing applications. Among of the high-performance commercial systems, a great number of photopolymerizable compositions have been studied due to properties such as easy preparation, low cost, high diffraction efficiency with low energetic exposures, capability to obtain high spatial-frequency holograms and temporal stability. Moreover, in these systems the compositions can be modified in order to optimize the response of the material and also to obtain information related to the mechanism of grating formation. The aim of this work is to investigate the effect of the addition or substitution of several components (coinitiator and photoinitiator) in a photopolymerizable holographic material based on a pyrromethene dye (PM567) acting as a photoinitiator and HEMA as monomer both of them dissolved in a dry polymeric matrix of PMMA. For this, diffraction gratings were recorded at different intensities and the energetic evolution of the diffraction efficiency as well as the observed inhibition period were studied as a function of the component that has been modified (coinitiator (tert-butyl peroxybenzoate (tBPH)) or photoinitiator PM546 and PM556). Moreover, the experimental angular selectivity curves were theoretically analyzed by the model of Kubota and Uchida, and as a result information such as the effective thickness, fringe bending and non-uniform index modulation against the thickness of grating was obtained. It is observed that when PM546 is used instead of PM567, better responses at a wide range of intensities are obtained, in particular at high intensity where gratings with low fringe bending and a relative constant index modulation against thickness is reached. When a coinitiator such as tert-butyl peroxybenzoate (tBPH) is added to the reference composition, shorter inhibition periods are obtained with low fringe bending but with lower diffraction efficiencies. Furthermore, as the reference system, the better response is given at low recording intensity. Finally, it is important to point out that with these compositions non-ideal energetic variations of the diffraction efficiency are observed. In this work we propose that these non-ideal curves can be explained by the effects related to the recorded non-uniform gratings. For this, by introducing the energetic variation of the index modulation and the fringe bending in the theoretical treatment of Kubota and Uchida a qualitative description of the experimental energetic diffraction efficiency curves can be obtained.

8074-32, Poster Session

Multiplexed holographic reflection gratings in Sol-Gel

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Holography is an attractive approach for obtaining structures with a periodic modulation in the refractive index. These periodic structures are the basis for diverse current and future applications such as the field of optical data storage technologies. Among the different methodologies for holographic storage one of them is hologram multiplexing in reflection geometry. In this work, the multiplexing of holographic reflection gratings with a spatial frequency higher than 5400 lines/mm in photopolymerizable sol-gel materials is experimentally demonstrated. The sol-gel matrix was prepared using a typical sol-gel technique and after this, the obtained glass was photosensitized by immersing it in a photosensitive solution, whose composition was; acrylamide, N-benzyl methacrylamide and N,N'-methylenebisacrylamide as monomer, triethanolamine as coinitiator and methylene blue as photoinitiator.

When the photosensitive solution was homogeneously distributed inside the porous material, the photosensitive glass was allowed to dry. Holographic reflection gratings were recorded using the output from a diode-pumped, frequency-doubled Nd:YVO4 laser (Coherent Verdi V5) which was split into two beams and collimated to yield two plane-waves at 532 nm. The two beams, which were propagated in opposite directions, overlapped at the recording medium intersecting at an angle of 0^o and 133^o (measured in air) for the initial position. In order to study the performance of this material for angular multiplexing of reflection gratings we analyzed the effect of the angular separations of 1, 3 and 5 degrees for several exposure times. The total recording intensity was 450 mW/cm^2 and exposure times of 40, 60 100 and 200 ms were used for each angular step. Moreover, 9 reflection gratings are angularly multiplexed with diffraction efficiencies between 6 and 12% using an energy of 9 mJ/cm^2 in each exposure, resulting in a dynamic range M/# = 2.8.

8074-34, Poster Session

Technology of integrating diffractive elements into an image-matrix hologram

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The given work investigates a way of integrating Diffractive Optical Elements (DOE) in the structure of a protective image-matrix hologram. An important feature of the suggested method is simplicity of realization by some modification of the frames exposure software and full hardware compatibility with image-matrix technology. Unlike other methods, the suggested one does not require changing the optical scheme between transitions from recording holographic frames area to the DOE ones and vice versa. Any shape of DOE in the hologram approximated to the size of the frame is available. A DOE frame cannot contain any part of a holographic region due to the different method of exposure. The minimal size of one DOE pixel is about 3 micrometer. The method under discussion allows recording both binary (two-phase) and multilevel (multi-phase) DOE at corresponding calibrations of the employed Spatial Light Modulator (SLM). The method has passed experimental approbation and is now used for embedding DOE into an image-matrix hologram as an additional security element.

8074-35, Poster Session

Design and research of parameters of an objective of the ultrahigh resolution for producing HOE-DOE by a method a dot-matrix

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The DOE-HOE, security holograms made by dot-matrix technology, have found the application in various areas, such as protection of the various goods and securities, packing etc. These elements and holograms contain set of pixels with various spatial frequency and orientation diffraction gratings.

Process of manufacturing represents consecutive pixels exposure. The pixels quantity is great (about 105-106), that's why there is a problem of considerable time to master-shim manufacturing. Spatial frequency and orientation of gratings changes because of mechanical moving of elements. For acceleration of recording process it is necessary to replace slow mechanical devices with high-speed ones. One of variants of this problem solution, using spatial light modulator, is given in proposed article.

Optical system configuration of the stand for DOE-HOE producing is consist a radiation source He-Cd laser, the expanding optical system forming required size of weakly convergent laser beam to illuminate liquid crystal spatial light modulator (LC-SLM). The weakly convergent laser beam is focused in front focal plane of special projecting objective. The special objective projects pattern from LCSLM to the photoresist plate, forming pixels with desired size and shape. The diffraction pattern after LCSLM is very complicated. The special spatial filter is placed to special projecting objective front focal plane. It filters only the +1 and the -1 orders of the diffraction beams to pass through the special projecting objective. Finally, these beams will converge and interfere to form holographic diffraction gratings on photoresist plate.

Before projective objective calculation it will be useful to consider the observation scheme of diffracted from DOE-HOE radiations. It will allow to define necessary values of the maximal and minimal spatial frequencies on a plate with photoresist and the quantization step of spatial frequencies.

From experience of optical systems calculation the magnification smaller, than 1/200, is unprofitable to use (manufacturing of objectives with smaller magnifications it is very labour-consuming and expensive). Thus we shall accept, that the magnification of projective objective makes = 1/200, then the quantization step of spatial frequencies $\Delta\nu$ph = 80 mm-1. This paper contains the techniques and results of optical components parameters calculations.

Knowing requared parameters, let's calculate the period and spatial frequency of holographic diffraction grating on a photoresist plate, and also wave length and color of diffracted light in an eye of the observer at $\theta = 30°$.

However, it is necessary to notice, that all calculations are lead for the size of pixel 28 10-3 , and it is the size of a diagonal. Diffraction occurs on the elements being sides of pixel. Thus, for the smaller side of pixel (8,4 microns) and for the period consisting of 26 pixels, we receive the period holographic lattices 0,546 microns.

Thus, the projective objective has following parameters:

- linear magnification β = 1/200; f ' = 4,287 mm
- a linear field in subject space 2y = 14 mm;
- front aperture A = 0.002022; back aperture A ' = 0,4044;
- the value of wave aberration should make /4;
- the objective contains the specialized spatial filter in a front focal plane.

The main element of the scheme is the special objective intended for coherent projection with a spatial filtration. Calculation of required magnification is lead. Calculation consist in a finding of an optimum ratio between quantity of LC-SLM pixels using to form one period of diffraction grating, the size of LC-SLM pixel, the required quantization step of spatial frequencies in the final image and magnification of an projective objective.

Also overall calculation of a laser beam expanding system, which forms weakly converging beam, has been lead. Parameters of an objective of an expanding system are determined.

8074-36, Poster Session

Optic-electronic system "HOLOINID" for automatic individualization and identification of security holograms

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With growth of volume of manufacture of security holograms (SH) the requirement for devices and monitoring systems of authenticity SH, and also their individualization grows also. As a new security element the latent coded microimage in the form of set of optical points (bits) has been chosen. The given image individually is brought in the hologram by means of laser micropunching at final production phase SH after duplicating. The given security element differs on different SH, that will allow not only to supervise authenticity of holograms, but also to distinguish one hologram from another.

Developed optic-electronical system GOLOINID includes the laser micropuncher for individualization SH and the optic-electronical device of reading of microimages and identification SH. The specialised software allows to operate the laser micropuncher, to process received by means of the optic-electronical devices of reading of the microimage on certain algorithm and to make the decision on authenticity SH. The laser micropuncher for an individualization of security holograms works at the expense of high density of capacity of laser radiation in the focused stain in a layer of metallized thermovarnish coat SH. The latent coded microimage represents set of a set of optical bats which make an information field, and reference objects for capture and image processing. The sizes of optical points (bits) usually make 50 microns, and the period between micron points-70 microns. Advantage of the laser micropuncher to individualization SH is that it is capable to receive the latent coded microimage in holograms not destroying blankets of holograms. It is reached at the expense of use in the micropuncher short-focusing of optics.

The technology Know-how consists in possibility of laser micropunching as in a layer of a thermovarnish which lays between layers of lavsan and the metallized layer (for self-glued SH), and in possibility of laser micropunching is direct in the metallized layer (for SH on a foil of a hot stamping).

The optiko-electronic device of reading of microimages for identification SH works as follows. SH with the microimage it is highlighted by not coherent source of radiation and it is projected by an objective on a photosensitive platform of a microvideocamera, signals with which are deduced in the personal computer. The received

image is processed by means of the specialized software on certain algorithm and the decision on authenticity SH is passed.

Developed optiko-electronic complex HOLOINID works with SH, put on plastic cards of the standard size 85,6   51 mm. Thus time of reception of the latent coded image in the size 6 12 information points has made 10 s, and time of identification of the protective holograms with the microimage of such size punched on it has made 1 s.

8074-37, Poster Session

Axial intensity distribution of converging spherical wave behind an elliptic aperture

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Off-axis holographic optics operates with beams having elliptic cross sections. It is the case of single-element holographic collimators for collimation of optical beams generated by edge-emitting diode lasers. Such collimators can transform elliptic cross-sectional diverging beams into collimated beams with the circular cross-section. In a reverse operation, collimated circular beams are transformed into elliptic converging beams. Focusing properties of that beams differ from beams having the circular aperture. Axial intensity distributions of converging spherical waves behind elliptic apertures are analyzed. Similarly to behaviour of circular cross-sectional beams, main maxima of the diffraction intensity move from the geometric focus to the location of the aperture with decreasing the Fresnel number. E.g., the main maximum is located at the half distance between the aperture and the geometric focus when the Fresnel number is 1 and the ellipticity index is 75 deg. On the other hand, for Fresnel numbers higher than 10 the displacement is insignificant. Displacements and values of the maxima are higher than for beams with the circumscribed circular aperture. Minima of curves do not achieve zero values as expected. All results can be given for specific parameters in numerical calculations only.

8074-38, Poster Session

Development of the next-generation optical holographic photovoltaic concentrator

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Photovoltaic (solar) energy conversion will provide a crucial part of future sustainable energy needs. The main issue currently facing the solar industry is how to reduce power generating system cost. The next-generation photovoltaics should aim at high efficiency but also lost-cost per unit area. Various approaches include replacing expensive semiconductor material with low cost solar collectors and concentrators and the use of high efficiency smaller area photovoltaic devices. The cost of electricity produced by photovoltaic solar cell can be reduced by concentrating the energy of the sun onto fewer cells and by utilizing more of the solar spectrum by splitting the spectrum onto cells individually optimized for a small portion of the solar spectrum. This work proposes the idea and underlying theory of optical holography and its applications in solar energy concentrations without the help of tracking system. Two improved devices of converting solar energy into electricity will be constructed. The first device consisted of a hologram pairs with a holographic splitter and a holographic optical element will spread the solar spectrum and concentrating it onto solar cells that are band-gaped in the corresponding wavelength range. The second ones consisted of a hologram paired with a holographic collimation device and a holographic Fresnel lens can be manufactured which will split the solar spectrum into multiple small portions of the solar spectrum and optically redirect the spectral bands onto multiple junction cells with the appropriate band-gap.

8074-39, Poster Session

Recording characteristics of holographic memory-using a co-axis type dual-reference beam

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The rapid progress in computer performance and widespread use of broadband networks has facilitated the transmission of huge quantities of digital information, thus increasing the need for high-speed, large-capacity storage devices and leading to studies on holographic data storage (HDS). As holographic recording media, photopolymer has great advantages that are high photosensitivity and image stability. But the shrinkage in photo-polymerization and the expansion or reduction via temperature change induces the rotation of the grating and a change in the grating period. These changes follow the shift from the Bragg condition and the decrease in the SNR. In this paper, we numerically show the simulation method of both the reflection and transmission type hologram recording and discuss about an influence of media shrinkage on signal quality. Also in our paper, dual-reference beam hologram recording method is proposed to improve the signal-to noise ratio.

The data multiplexing of our system is achieved by angular multiplexing. In this system co-axis type dual-reference beam is prearranged in the recording system. This structure takes advantage of the fact that high-performance and small-size optical head can be achieved. The reference beam is split into a dual-reference beam by small size prism beam splitter. Angular servo at reproduction is easily achieved by one demententional movement of prism beam splitter in our optical system.

We studied both one reference beam recording and co-axis type dual-reference beam hologram recording. In our simulation model, to satisfy the conditions of scalar diffraction calculation, the hologram medium is divided into sufficiently thin layers in the optical axis direction, and a series of calculations is made by angular spectrum analysis for each layer at recording and reproduction. By using these analysis, the amplitude of the holographic reproduction image is obtained on the imager plane.

By our simulation analysis, it is cleared that if the media shrinkage occurs 0.1%, the best reference beam angle changes about 0.03 degree at one reference beam recording. If co-axis type dual-reference beam is used, the best reference beam angle do not change even if media shrinkage occurs at perpendicular direction.

In this paper, the experimental results of holographic recording characteristics for a one reference beam and a dual-reference beam are also discussed. The film thickness of photopolymer is 100μm and the second harmonic of a yttrium aluminum garnet(YAG) laser is used for the recording /reproduction. These experimental results agree with simulation results in high precision.

8074-40, Poster Session

Reduction of zero-order spatial frequencies by using binary intensity and phase modulations in holographic data storage

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In the present society new storage technologies are very important because they provide more capacity, higher density and faster data transfer, and enable more efficient data search. Conventional optical memory technologies, two-dimensional surface-storage-based (like CD-ROMs and DVDs) have almost arrived at the limit of their capacity and they are becoming obsolete. In recent years there has been a focusing on the development of holographic storage techniques, in which information is not stored on the surface of the material, but in the volume. Holographic memories promise to increase storage density with higher reading speeds partly due to the inherent parallelism in the pursuit of information, and a very attractive and unique property, such as associativity allowing searches by content in parallel in all the memory.

For holographic data storage, liquid crystal displays (LCD) are used as spatial light modulators which introduce the information to be stored in the material. This information is stored by holographic techniques with the interference between the Fourier Transform (FT) of the object beam and a reference beam. In general, Binary intensity (BI) modulation is commonly used for the information sent to the LCD. However, this type of modulation produces a high zero spatial frequency in the Fourier plane with an intensity several orders of magnitude higher than the other frequencies. As a result, the dynamic range of the material is saturated, limiting the storage capacity. The problems caused by the lack of homogeneity in the spectrum can be solved by using some other modulation schemes, such as binary phase modulation (BP), or storing a slightly blurred version of the FT through defocusing when the BI modulation scheme is used.

This paper analyzes the behaviour of these two modulations and compares the results obtained to see what modulation could be the most suitable for holographic data storage. To this end, two important parameters are compared to optimize holographic data storage: the Bit Error Rate (BER), which gives us an idea of the fidelity of information stored, and a parameter of homogeneity of the FT, which takes into account the finite dynamic range of the material. Different aspects of a realistic experimental setup are considered in the simulation, such as the finite aperture in the recording plane and the complex amplitude modulation capabilities of actual LCDs.

8074-41, Poster Session

Compact slot-in-type optical correlator for retrieving shape, color, and texture

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We have realized a compact optical correlator applicable to the retrieval of color and texture as well as shape information. Optical correlator can retrieve only shape information and cannot be directly applied to the retrieval of color- and texture-information. The new technique retrieving color and texture information was developed using a slot-in-type compact joint transform correlator (JTC) having the minimum size, 140 mm (W) × 220 mm (L) × 40 mm (H). This correlator can be installed in the cabinet of commercial personal computers.

The color information taken by a digital camera was transformed to two-dimensional color patterns on the color chart, and each pattern was retrieved on the JTC system. The luminance information from the digital camera was transformed to two-dimensional histograms in corresponding to the luminance intensity, and the shape of the histogram was retrieved since the skewness of the luminance histogram was reported to correlate with surface gloss and lightness in the texture. By using the techniques developed in this study, the pictures of fruits and vegetables, which were taken by the digital camera, were retrieved after transforming to color patterns and luminance histograms. The two-dimensional patterns were displayed on an input plane and retrieved on the JTC system. A certain fruit, such as an apple, could be well retrieved from many fruits and vegetables on the system.

The compact optical correlator and new techniques developed in this study provide retrieving procedures with high accuracy and will be applicable to apparatus for human visual information processing. This system will be able to open a new technological stage of visual information processing.

8074-42, Poster Session

Research of properties of the holographic screen

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The holographic screen (HS) is intended for use in 3D-displays. HS it is made as the hologram of a converging light wave and by itself the picture of an interference of basic and subject bunches registered on the registering environment in a kind diffraction gratings with variable step. At a projection to such screen of the colour image owing to inherent such lattice of an angular dispersion with differing for various lengths of waves the problem of perception the observer of not deformed colour image as zones of supervision for each site of a spectrum appear displaced in supervision space arises values of this dispersion.

The problem dares by use at record HS of a subject bunch from set of dot sources, i.e. record in the necessary direction diffuser. At work such HS the zones of the supervision providing not deformed perception full color of the image, settle down in the field of imposing images of pupils of the projectors corresponding to various spectral components of bunches of radiation of projectors.

For formation of the image as a part of the display various projectors can be used: videoprojectors on a basis LCD - or DMD-panels etc. Thus can be looked through volume images both static, and dynamic scenes, for example, in the form of video films at corresponding synchronisation of streams of the information arriving on projectors from external sources.

The presented experimental sample of the display has following basic characteristics:

- The size of the screen on a diagonal - 15 inches;

- The permission to the screen - 400-600 points on a vertical and a horizontal;

- Removal of zones of supervision from the screen - 1,5 m;

- A temperature range of operation - from-20 With to +60 With.

On the basis of the offered methods and technologies probably creation of 3D-displays with the improved characteristics, first of all, concerning the sizes of the screen (to 22 inches and more) and numbers of observable foreshortenings (to 2 and more) with increase accordingly numbers of pair zones of supervision.

8074-43, Poster Session

Coupled-wave theory analysis of holographic structures for slow-light applications

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Recently, a great interest has been paid on the ability to slow down the propagation of light due to their potential applications in the field of Photonics. For this, Electromagnetically Induced Transparency (EIT) resonances, Coherent Population Oscillation, atomic double resonances, Photonic crystals waveguides, coupled resonator optical waveguides (CROWs) and Stimulated Brillouin Scattering (SBS) in optical fiber have been used for studying the reduction of group velocity. In this work we are going to theoretically analyze Holographic periodic structures obtained by sequential multiplexing techniques in order to modify the propagation group velocity. The study of slow-light effects on these designed structures has been performed by analytically obtaining the transmission spectrum function by using the coupled wave theory. After sequencial multiplexing of two gratings, the reconstructed wave (R[z]) is obtained by solving the differential equation:

d^3 R[z]/dz^3 + alfa d^2 R[z]/dz^2 + beta d R[z]/dz + gamma R[z] =0 with boundary conditions given by:

R[0]=1, (dR[z]/dz)|z=L =0, (d^2 R[z]/dz^2)|z=L = psi R[L]

Transmission function (T) is obtained as:

T=R[L]

From the conditions of transmittance equal to 1 for the designed frequency, the geometrical design parameters and material properties have been obtained. By using these values, the time delay is studied, analyzing the influence of the variations of the geometry and material parameters.

Conference 8075: Harnessing Relativistic Plasma Waves as Novel Radiation Sources from Terahertz to X-rays and Beyond

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8075-01, Session 1

Laser-induced relativistic quantum dynamics and quantum electrodynamics

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Laser-driven relativistic quantum dynamics is discussed for bound and free electrons [1,2]. Applications such as the generation of harmonics and short pulses is discussed and compared to other means [3]. Then emphasis is placed on situations where the influence of vacuum fluctuations is shown to become observable with present facilities or those under construction, especially on the concept of a matterless double slit [4]. In the following, pair production is investigated in strong laser fields, especially with the aid of other injected particles [5]. At the end applications are pointed out such as investigating highly charged ions with XFEL light [6] and generating fast ions with strong laser fields for medical purposes [7].

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8075-02, Session 1

Analytical model for QED cascade development in rotating superstrong electric field

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Quantum electrodynamics (QED) cascade (or electromagnetic cascade) is an avalanche-like multiplication of energetic electrons, positrons and photons in strong electromagnetic field. For example, such cascades can arise in rotating electric field of the B-node of the electromagnetic field of colliding laser pulses. Electron or positron accelerates in a such field and emits hard photons. These photons can, by turn, decay with creation of electron-positron pairs. The cascade can be initiated by a single pair created accidentally from the vacuum in the laser field or by external high-energy photons.

We present the analytical model that allows us to obtain spectra for high-energy particles. The model is based on solution of equation for particle distribution functions. The obtained results can be used for the planning of future experiments and analysis of experimental data.

The results of numerical modeling of QED cascades are also discussed.

First, the analytical results are in a good agreement with results of numerical simulation. Furthermore, it is shown by the means of numerical simulations that ultrarelativistic electron-positron pair plasma with particle density exceeding the solid-state one can be produced by colliding laser pulses in vacuum. A significant part of laser energy is scattered and absorbed by the self-generated electron-positron pair plasma that can limit the attainable intensity of the focused laser radiation. Furthermore, the plasma can be used as a bright source of high-energy gamma-quanta.

8075-03, Session 1

QED effects and radiation generation in relativistic laser plasma

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In the last decades, the progress in laser technology has opened up new opportunities for high field physics. When the matter is irradiated by intense laser pulses hot and dense plasma is produced. The relativistic laser plasma is a unique source of ultrahigh fluxes of photons and particles in very short duration pulses. Moreover, upcoming high power laser facilities like ELI (Extreme Light Infrastructure) will reach new intensity frontiers when physics phenomena, which has not been explored so far, like radiation reaction and QED effects come into play. Recently a much attention is attracted to the development of the electromagnetic cascades in intense laser fields. The cascade development can be illustrated as follows. An electron or positron can be very quickly accelerated by the laser field to relativistic energies and emits hard photons, which can decay in laser field and produce new generation of electron-positron pairs. It turns out that the electron-positron pair plasma produced via development of the electromagnetic cascade can efficiently absorb the laser energy and can limit the attainable intensity of high power lasers. Furthermore, the electromagnetic fields of self-generated electron-positron pair plasma can affect the cascade developments.

To study QED processes in laser plasma we develop self-consistent numerical model based on particle-in-cell and Monte-Carlo methods. First we analyze the radiative losses in plasma-based accelerators and betatron radiation generation in classical and quantum regimes. Then we address an interaction between intense laser pulse and relativistic electron beam with application to Compton radiation source. Finally we discuss the electron-positron pair plasma production in extremely-intense laser field. It is shown that such plasma can be an efficient source of energetic gamma-quanta.

8075-04, Session 1

Classical and quantum radiation reaction effects in intense laser fields

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A fundamental problem in electrodynamics is the so-called “radiation reaction” problem: classically, when a charged particle (an electron, for definiteness) is accelerated by an external field, it emits radiation and this emission changes the motion of the electron. In the realm of classical electrodynamics, the so-called Landau-Lifshitz (LL) describes the motion of an electron by including the effects of radiation reaction [1] and it has not yet been tested experimentally. We explore a new regime of parameters in which, as predicted by the LL equation, the influence of radiation reaction on the electromagnetic spectra emitted by an electron in the presence of an intense laser field is substantial [2].

What is the quantum analog of radiation reaction? In [3] we have answered this question identifying quantum radiation reaction with the multiple photon recoils experienced by the external-field-driven electron due to consecutive incoherent photon emissions. Also, we investigate the quantum radiation dominated regime, in which quantum recoil and radiation reaction effects both dominate the dynamics of the electron. We show that present laser and electron accelerator technologies allow in principle the possibility of realizing this regime experimentally.

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8075-05, Session 2

High field science for novel radiation sources

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Relativistic plasma waves are an ideal tool to drive novel brilliant and/or coherent radiation sources. Whys is this? It is believed that this strong tie between the above two arises from the fundamental nature of relativistic optics. In relativistic plasma waves we enjoy the property that the relativity disallows electrons to exceed the speed of light and thus it helps the relativistic coherence emerge. This is an interesting and sharp contrast with quantum coherence in quantum optics. In more general sense we (Gerard Mourou and I) recognize that the layer of nonlinearities of matter provides the reason why the pulse length can be shortened if and when we employ greater intensity of laser to drive coherent radiation from matter. This Conjecture guides us to use high intensity lasers (and thus high field science) to further explore novel radiation sources with coherence. The more intense the laser becomes, the shorter pulses we can acquire in producing coherent radiation. We present some recent examples of the above.

8075-06, Session 2

QED and nuclear physics based on intense laser fields and gamma ray radiation emanating from plasma

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No abstract available

8075-07, Session 2

Nuclear dynamics in intense laser fields

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The development of coherent light sources in the optical regime has boosted atomic physics and quantum optics in the last decades, opening new directions towards control of the atomic dynamics. In nuclear physics, coherent control of nuclear excitations has been a long-time goal, as it is related to a number of promising applications such as nuclear quantum optics [1], including isomer depletion [2] or the problem of gamma ray lasers. However, nuclei proved to be much more difficult to control, due to the lack of coherent gamma ray sources and the more complicated underlying internal nuclear structure. Radiation arising from laser-plasma interactions is providing novel light sources that may extend the range of applications of electromagnetic radiation also to control nuclear dynamics.

Inspired by atomic quantum optics techniques, we address here the direct interaction between x-ray lasers and nuclei. In particular, we investigate the possibility of coherent nuclear population transfer between two ground states in a Lambda level scheme using two overlapping coherent x-ray light beams in a stimulated Raman adiabatic passage setup [3]. We show that with temporally coherent pump and Stokes laser fields, and acceleration of the target nuclei to achieve the resonance condition, significant coherent nuclear population transfer is achieved at intensities within the present designed values of x-ray free electron lasers. As relevant application, the controlled pumping or release of energy stored in long-lived nuclear states is discussed.

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[2] A. Palffy, J. Evers and C. H. Keitel, Phys. Rev. Lett. 99, 172502 (2007)

[3] W.-T. Liao, A. Palffy and C. H. Keitel, arXiv:1011.4423 (2010)

8075-08, Session 2

Radiation friction modeling in superintense laser-plasma interactions

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Radiation Friction (RF) effects are important for highly relativistic electrons in superintense electromagnetic fields and are thus expected to play a crucial role in next-term experiments. It is therefore important to include RF in particle-in-cell (PIC) simulations of laser-plasma by an appropriate modeling, keeping the essential RF effects into account while retaining at the same time the capability to perform large-scale simulations. We describe a suitable approach, based on the Landau-Lifshitz equation, which allows the insertion of RF in PIC codes in a modular way and with a very reduced computational cost [1]. Properties of the kinetic equation with RF which is effectively solved by the PIC method are also discussed [2]. We then present the results of multi-dimensional PIC simulations, mainly on radiation pressure acceleration of thin foil targets, addressing the importance of RF effects and showing the strong role played by the laser pulse polarization.

[1] M. Tamburini, F. Pegoraro, A. Di Piazza, C. H. Keitel, A. Macchi, New Journal of Physics 12, 123005 (2010); arXiv:physics/1008.1685 .

[2] M. Tamburini, F. Pegoraro, A. Di Piazza, C. H. Keitel, T. V. Liseykina, A. Macchi, arXiv:physics/1011.5635.

8075-09, Session 3

Cascade mechanism of particle creation in super strong laser fields

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The effect of e+e- pair creation in vacuum by a super strong laser field is discussed. It is shown that the effect becomes observable experimentally at laser intensities I ~ 5 1025 W/cm2. At such intensities even a single pair created by the laser field would cause development of an avalanchelike QED cascade. There exists an important distinctive feature of the laser-induced cascades, as compared with the air showers arising due to primary cosmic ray entering the atmosphere. In our case the laser field plays not only the role of a target (similar to a nucleus in the case of air showers). It is responsible also for acceleration of slow particles. A simple qualitative model for description of such type of cascade is developed. The qualitative estimations are confirmed by the results of Monte-Carlo simulations. It is shown that the cascade initiated by created pairs rapidly depletes the incoming laser pulse. This confirms the Bohr's old conjecture that the electric field of the characteristic QED strength ES=m2c3/e could never be created.

8075-10, Session 3

Non-linear electrodynamics in plasmas

D. A. Burton, Lancaster Univ. (United Kingdom)

The forthcoming generation of ultra-intense lasers are expected to have field intensities that may permit controllable investigation of the QED vacuum. Detailed theoretical analysis of the behaviour of intense laser-plasmas in such regimes is currently incomplete; for example, Schwinger's classic analysis of vacuum breakdown in a static external electric field is not immediately applicable to the dynamical and

non-uniform field of an intense laser pulse. Although there is some indication that the field intensity threshold for triggering significant electron-positron pair production may be 1-2 orders of magnitude lower than the Schwinger limit, tractable models for reliable analysis of non-perturbative quantum vacuum phenomena have not yet been established for such laser-plasmas.

It is likely that tractable models will be semi-classical rather than fully quantum, and effective theories of non-linear electrodynamics will play a central role. Such theories must include radiation-reaction, and negotiate the pathologies exhibited by the Lorentz-Dirac equation in Maxwell electrodynamics. In particular, there is much current interest in Born-Infeld theory as it is expected to resolve the radiation-reaction problem and is present in low-energy string field theory.

We will summarize Born-Infeld electrodynamics and explore its implications for intense laser-plasmas by investigating properties of large amplitude Born-Infeld plasma waves.

8075-11, Session 3

Relativistic laser plasmas for novel radiation sources

A. Pukhov, Heinrich-Heine-Univ. Düsseldorf (Germany)

The presentation will address betatron radiation and on HHG from overdense surfaces.

8075-12, Session 3

High-energy laser pulse propagation in plasma: photon acceleration and self-focusing effects

Y. Kravets, Univ. of Strathclyde (United Kingdom); A. Cairns, Univ. of St. Andrews (United Kingdom); B. Ersfeld, A. Noble, R. Islam, G. Raj, D. A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

The interaction of intense electromagnetic fields with matter is currently an important area of research. In many cases the propagation of an intense laser pulse in plasma plays an important role. Here we present an analysis of pulse propagation using the ray tracing method, which includes relativistic and ponderomotive self-focussing, and photon-acceleration and deceleration. This work is relevant to the evolution of the laser pulse in laser plasma wakefield accelerators operating in the bubble regime.

8075-14, Session 4

Raman amplification of long laser beams to kilojoule energies and petawatt powers

R. M. G. M. Trines, R. Bingham, P. A. Norreys, Rutherford Appleton Lab. (United Kingdom); F. Fiuza, R. A. Fonseca, L. O. Silva, Univ. Técnica de Lisboa (Portugal); A. Cairns, Univ. of St. Andrews (United Kingdom)

The demonstration of fast-ignition (FI) inertial confinement fusion (ICF) requires the delivery of 40 kJ - 100 kJ of laser energy to the hot spot within 16 ps, assuming that the energy conversion from laser beams to fast electrons is in the range 20% - 50%. In addition, it is necessary to optimise $Ilambda^2$ to ensure that the hot electron energy falls within the correct range for stopping of the fast electrons, implying third harmonic conversion to 351 nm. High-energy picosecond petawatt beams at 351 nm are extremely difficult to generate using conventional solid-state laser systems.

Previous studies of Raman amplification have concentrated on reaching the intensity frontier, which requires ultra-short pulses in the femtosecond regime [1]. Here we present novel particle-in-cell simulations, supported by analytic theory, that confirm that Raman amplification of high-energy nanosecond pulses in plasma can generate efficient petawatt peak power pulses of picosecond duration with high conversion efficiency (up to 60%), even at 351 nm wavelength [2]. This scheme provides a new route to explore the full parameter space for the realisation of the fast ignition inertial confinement fusion concept in the laboratory. This work also opens up a wide range of other high energy density physics research applications, including monochromatic K$_alpha$ x-ray, proton beam and Compton radiography of dense plasmas, among many others.

[1] R. Trines, F. Fiuza et al., Nature Physics 7, 87 (2011).

[2] R. Trines, F. Fiuza et al., ArXiv 1102.0460 (2011).

8075-15, Session 4

Chirped pulse amplification based on Raman backscattering in plasma

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Raman backscattering (RBS) in plasma is an attractive source of intense, ultrashort laser pulses, which have the potential of bringing in a new generation of laser amplifiers. Taking advantages of plasmas than can withstand extremely high power densities and can offer high efficiencies over short distances, Raman amplification in plasma could lead to significant reductions in both the size and cost of high power laser systems.

Experiments aiming to develop an effective way to transfer energy from a long chirped pump pulse to a resonant counter-propagating short probe pulse in a preformed plasma capillary have been carried out at the University of Strathclyde. A study of the properties of RBS in plasma has been undertaken for different pulse durations and laser energy levels. Complete temporal information on the probe pulse both before and after amplification have been obtained using the Frequency Resolved Optical Gating (FROG) technique.

8075-16, Session 4

Wavebreaking as a limit for Raman amplification

J. P. Farmer, B. Ersfeld, G. Raj, D. A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

Raman amplification in plasma has been suggested as a method for creating ultra-short, ultra-intense laser pulses for use in a wide range of science and technology applications, such as the laser wakefield accelerator.[1] Plasma offers the advantage that, unlike conventional amplification media, it is not subject to thermal damage. This avoids the need to use Chirped Pulse Amplification, which required gratings that can be large and expensive at high powers.

However, wavebreaking of the Langmuir wave reduces amplification thus imposes a limit on the attainable powers. Most studies to date have investigated the cold wavebreaking limit, which can be many times higher than that for warm plasma.

While it is well known that higher plasma densities can be used to raise the wavebreaking limit, this in turn leads to other problems such as Raman Forward Scattering.[2] We investigate, through the use of particle-in-cell simulations, regimes in which wavebreaking is important. We identify the limits that these lower wavebreaking thresholds impose and how to avoid them. Wavebreaking can, in certain situations, be beneficial, by allowing a superradiant-like amplification without significant pump depletion, thus making this regime suitable for multi-pass systems.[3]

[1] G. Shvets, N. J. Fisch, A. Pukhov and J. Meyer-ter-Vehn, Phys. Rev. Lett. 81, 4879 (1998)

[2] J. Ren, W. Cheng, S. Li and S. Suckewer, Nature Physics 3, 732 (2007)

[3] R. M. G. M. Trines, F. Fiúza, R. Bingham, R. A. Fonseca, L. O. Silva, R. A. Cairns and P. A. Norreys, Nature Physics, doi:10.1038/nphys1793 (2010)

8075-17, Session 4

Efficient Raman amplification into the multi-PW regime

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The advent of high power lasers is allowing for the exploration of a wide range of nonlinear phenomena of interest for many applications such as fast ignition of fusion targets or compact plasma-based accelerators. The laser architectures being considered for upcoming ultrahigh intensity laser facilities are based upon solid state lasers which are very successful in providing petawatt peak powers to target. However, the breakdown threshold for optical components in these systems demands meter-scale beams. For a number of years, Raman amplification has promised a breakthrough in laser beam compression at ultrahigh intensity via the use of much smaller amplifying media, i.e. millimeter diameter wide plasma, but to date, only 60 GW peak powers have been obtained in the laboratory.

We show, through the first large scale multi-dimensional particle-in-cell simulations of this process, that multi-petawatt peak powers can be reached, but only in a narrow parameter window dictated by the growth of plasma instabilities. The control of these instabilities promises greatly reduced costs and complexity on intense lasers, allowing much greater access to higher intensity regimes for fundamental science and industrial application. Furthermore, it is shown that this process scales to short wavelengths allowing compression of X-ray free electron laser pulses to attosecond duration.

8075-35, Session 4

Raman amplification in plasma

A. Cairns, Univ. of St. Andrews (United Kingdom)

Raman scattering in a plasma is a three-wave interaction in which an electromagnetic wave transfers energy to another electromagnetic wave at lower frequency and to a Langmuir wave. To be e?ective this requires that the resonance condition, that the frequency and wavenumber of the first wave be the sum of those of the other two, is at least approximately satisfied. This process has long been studied as something which may have an adverse affect on schemes to produce laser compression of targets since it can lead to backscattering of some of the incident radiation. More recently it has been proposed that it might be used to produce amplification of a short pulse in a plasma, the hope being that it might be a way towards generating very high intensities while avoiding the problems of damage to conventional optical components. The basic idea is that a long pump pulse transfers energy to a counter-propagating short seed pulse at slightly lower frequency. In an underdense plasma, where the plasma frequency is much less that the wave frequency, the energy also transferred to a Langmuir wave is small and, if a regime is reached in which the pump wave is strongly depleted, there can, at least in principle, be efficient amplification of the short pulse. I shall discuss the basic ideas behind this amplification scheme and some of the e?ects which may limit the growth of the short pulse.

8075-18, Session 5

Progress on a XUV free electron laser driven by a laser plasma accelerator

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Experiments are underway at LBNL to demonstrate the possibility of driving an extreme ultraviolet free electron laser using an electron beam produced by a laser plasma accelerator. A channel guided structure with longitudinally controlled density profile is used to generate 100-400 MeV beams. These beams are then transported into a 1.5 m long undulator where radiation is generated. The radiation is measured with a broadband XUV spectrometer. Various diagnostics are employed to monitor the electron beam, including optical transition radiation, charge monitors and RF cavity based beam position monitors. The status and recent progress on the experiments will be reported. Supported by US DOE under Contract no. DE-AC02-05CH11231 and DTRA.

8075-19, Session 5

FEL or synchrotron source driven by LWFA

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No abstract available

8075-20, Session 5

A new XUV-source for seeding a FEL at high repetition rates

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Improved performance of Free Electron Laser (FEL) light sources in terms of timing stability, pulse shape and spectral properties of the amplified XUV/soft X-ray pulses is of interest in many fields of science. A promising scheme is direct seeding with High-Harmonic Generation (HHG) in a noble gas target. A Free-Electron-Laser seeded by an external XUV-source is planned for FLASH II (collaboration HZB/DESY). The requirements for the XUV/soft X-ray source can be summarized as follows: A repetition rate of at least 100 kHz (1 MHz upgraded) in a 10 Hz burst is needed at variable wavelengths from 10 to 40 nm and pulse energies of several nJ within a single harmonic.

This application requires a laser amplifier system with exceptional parameters, mJ-level pulse energy, sub-10 fs pulse duration at 100 kHz (1 MHz) burst repetition rate. A new OPCPA system is under development in order to meet these requirements, and very promising results has been achieved. In parallel to this development, a new High-Order Harmonic Generation concept is necessary to sustain the high average power of the driving laser system and for the need of high conversion efficiencies. Highest conversion efficiency in High

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Harmonic Generation has been shown using gas-filled capillary targets, up to now. For our application, only a free-jet target is applicable for high harmonic generation at high repetition rate, to overcome damage threshold limitations of HHG target optics. A new dual-gas multi-jet target was developed and recent results show a very good performance of this nozzle configuration, concerning spectral tunability and conversion efficiency.

The combination of the new Laser amplifier system and the dual-gas HHG target will lead to a unique XUV-source applicable for external seeding of FEL and for other high flux XUV/soft X-ray-experiments.

8075-21, Session 5

Coherent transition radiation as a tool for investigating bunches of electrons produced by laser wakefield accelerators

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The laser plasma wakefield accelerator can produce electron bunch that are 1-5 femtosecond in duration. These extremely short durations preclude using conventional methods such as electro-optic crystals or streak cameras to measure their lengths. However, coherent transition radiation emitted when charged particles cross the boundary between two different dielectric media, can be used to accurately determine the electron bunches parameters. We will show how an interference pattern in transition can be used to extract relevant parameters of the electron bunch, such as emittance, bunch duration and energy.

8075-22, Session 6

Towards a table top free-electron laser

M. P. Anania, E. Brunetti, D. Clark, S. Cipiccia, R. Issac, T. McCanny, A. Reitsma, R. P. Shanks, G. Welsh, S. M. Wiggins, Univ. of Strathclyde (United Kingdom); B. van der Geer, M. de Loos, Pulsar Physics (Netherlands); M. Poole, J. Clarke, B. Shepherd, Daresbury Lab. (United Kingdom); D. A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

Recent progress in developing laser-plasma accelerators is raising the possibility of a compact coherent radiation source that could be housed in a medium sized university department. Furthermore, since the duration of electron bunches from laser-plasma wakefield accelerators (LWFAs) is determined by the relativistic plasma wavelength, radiation sources based on these accelerators can produce pulses with femtosecond durations. Beam properties from laser-plasma accelerators have been traditionally thought of as not being of sufficient quality to produce amplification. However, our work shows that this is not the case. Here, we present a study of the beam characteristics of a laser-plasma accelerator and the compact ALPHA-X (Advanced Laser Plasma High-energy Accelerators towards X-rays) free-electron laser (FEL). We will present a study of the influence of beam transport on FEL action in the undulator, paying particular attention to bunch dispersion in the undulator. We will also show how the electron beam properties can be optimized to allow FEL lasing in the VUV region. We will also present simulations that have been performed using the beam properties measured on the ALPHA-X beam line. This is an important step for developing a compact synchrotron source or a SASE free-electron laser.

8075-23, Session 6

Laser-driven radiation sources in the ALPHA-X project

S. M. Wiggins, R. Isaac, G. Welsh, E. Brunetti, B. Ersfeld, M. R. Islam, G. Raj, A. Noble, G. Vieux, R. P. Shanks, S. Cipiccia, M. P. Anania, S. Chen, X. Yang, J. P. Farmer, S. Abuazoum, R. T. L. Burgess, G. Manahan, C. Aniculaesei, D. Grant, A. Subiel, Y. Kravets, R. Bonifacio, D. A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

The Advanced Laser-Plasma High-Energy Accelerators towards X-rays (ALPHA-X) programme is developing laser-plasma accelerators for the production of ultra-short electron bunches with subsequent generation of high brilliance, short-wavelength radiation pulses. Ti:sapphire laser systems with peak power in the range 20-200 TW are coupled into mm- and cm-scale plasma channels in order to generate electron beams of energy 100-800 MeV. Ultra-short radiation pulses generated in these compact sources will be of tremendous benefit for time-resolved studies in a wide range of applications across many branches of science.

Here we give an overview of radiation production studies being conducted in the ALPHA-X project. The two primary mechanisms of radiation production are (i) betatron radiation due to transverse oscillations of the highly relativistic electrons in the plasma wakefield and (ii) undulator radiation arising from transport of the electron beam through a planar undulator. In the latter, free-electron laser action will be observed if the electron beam quality is sufficiently high leading to stimulated emission and a significant increase in the photon yield. Other aspects of the project investigate the ion channel laser, gamma ray bremsstrahlung radiation and coherent transition radiation production. All these varied source types are characterised by their high brilliance arising from the inherently short duration (~1-10 fs) of the driving electron bunch.

8075-24, Session 6

X-ray imaging based on radiation sources driven by a laser plasma wakefield accelerator

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Experiments are currently being undertaken to prove that high quality electron beams from a laser plasma wakefield accelerated can be used to generate high brightness coherent radiation in the UV-VUV region in a free-electron laser based on a conventional undulator. However, a plasma channel produced by an intense laser pulse can also act as a very compact wiggler, where betatron radiation is emitted in ultra-short, spatially coherent, pulses with photon energies extending from the soft x-rays to gamma rays by an electron beam while it is being accelerated. These sources are promising for phase-contrast x-ray imaging applications, where high definition, microscopic, images of weakly absorbing material with improved edge definition are required. Here we present an initial study of imaging in the VUV and x-ray spectral range.

8075-25, Session 6

Steady-state description of an ion channel free-electron laser with varying betatron amplitude

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The ion-channel laser (ICL) has been proposed as an alternative to the free-electron laser (FEL), replacing the deflection of electrons by the periodic magnetic field of an undulator with the periodic betatron motion in an ion channel. Ion channels can be generated by passing dense energetic electron bunches or intense laser pulses through plasma. The ICL has potential to replace FELs based on magnetic undulators, leading to very compact coherent X-ray sources. In particular, coupling the ICL with a laser plasma wakefield accelerator

would reduce the size of a coherent light source by several orders of magnitude.

An important difference between FEL and ICL is the dependence of the betatron frequency on the oscillation amplitude in the latter, while in the former the frequency of transverse oscillations is fixed by the undulator period.

We show how the ICL can be described in terms of the well developed formalism for the FEL, taking into account the dependence of the resonance between oscillations and emitted field on the oscillation amplitude. As a first step, we choose a steady-state description, neglecting slippage between electron and radiation phases. The resulting model equations are formally similar to those for the FEL with space charge taken into account, and a similar universal scaling can be applied, leaving a single independent parameter analogous to the rho-parameter of the FEL.

Numerical solutions for experimentally relevant parameters show similarities and differences between both devices in dependence of this parameter.

8075-26, Session 7

Bright spatially coherent betatron X-rays as wakefield diagnostic and radiation source

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We are reporting on recent laser wakefield acceleration experiments carried out with the 100 TW Hercules laser at the University of Michigan and the 200 TW Gemini laser at the Rutherford Appleton Laboratory.

Beams of relativistic electrons and keV x-rays are observed and characterized. Electron spectrum and beam profile as well as x-ray spectrum, beam profile and source size are measured. The x-ray beam is found to be synchrotron like, of small divergence, source size and with an appreciable degree of spatial coherence. X-rays are produced by the wiggling electron beam in the plasma wakefield, analogously to what would happen in a conventional permanent magnet insertion device. The x-rays can be used both as a diagnostic or radiation source, to learn about the dynamics of the accelerated electrons or to image biological specimen. [1,2]

[1] S. Kneip, et al., Phys. Rev. Lett., 100, 105006 (2008)

[2] S. Kneip, et al., Nat. Phys., 6, 980 (2010)

8075-27, Session 7

Betatron radiation from multi-PW lasers

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With the advent of multi-PW lasers the electron bunches generated in laser-wakefield accelerators in matched conditions will be able to reach over 10 GeV of energy. In this work we explore the possibilities opened by such systems on the radiation emitted by the electrons in the form of betatron radiation. Using the scalings for the matched parameters and the theoretical predictions for the betatron radiation we derive the parameter range for the radiation to be produced by 10 GeV self-injected electron beams. We illustrate these results with massivelly parallel PIC simulations coupled to the post-processing radiation code Jrad.

8075-28, Session 7

Traveling wave Thomson scattering: a source of X-ray photons with high per-shot yield and tunable energy and bandwidth

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Thomson sources, driven by laser-wakefield accelerated (LWFA) electrons or small linacs are compact in size and can provide ultrashort, hard X-ray pulses of high brilliance [1]. However, in head-on (180°) Thomson setups, the finite Rayleigh length at small interaction diameters ultimately prevents further advances in peak brilliance, since it becomes increasingly difficult to avoid the nonlinear Thomson regime.

Effectively, not the laser or electron properties, but the interaction geometry limits the performance of all future Thomson sources that aim for high single-shot photon yields.

In order to circumvent this bottleneck, we present a novel concept, which allows obtaining centimeter to meter long optical undulators, where interaction length and diameter are independent of each other.

With an ultrashort, high-power laser pulse in an oblique angle scattering geometry using tilted pulse fronts, electrons and laser remain overlapped while both beams travel over distances much longer than the Rayleigh length.

Such a Traveling-wave Thomson scattering (TWTS) design [2] is particularly interesting for future LWFA-driven Thomson sources with photon yields per pulse that can be orders of magnitudes beyond current designs. In addition, TWTS offeres unique advantages with respect to the minimum scattered bandwidth, which here is independent of the ultrashort laser pulse duration. Instead, it is controlled by the width of a cylindrically focused laser beam.

The possibility to freely choose a side-scattering angle -- from 0 to over 120° -- enables tuning of the photon energy without having to change the electron energy. For optimized LWFA electron sources operating within a narrow energy range, this opens up access to large parts of the X-ray spectrum and hence many applications.

Towards experimental realization, we show how a Traveling-wave setup has to be implemented. An emphasis is put on the use of varied-line spacing (VLS) gratings for dispersion precompensation of the laser beam at large interaction angles to achieve the required overlap between laser and electrons within the interaction region.

[1] A. D. Debus et al., Linear and non-linear Thomson-scattering x-ray sources driven by conventionally and laser plasma accelerated electrons, Proc. SPIE, Vol. 7359, 735908, 2009

[2] A. D. Debus et al., Traveling-wave Thomson scattering and optical undulators for high-yield EUV and X-ray sources, Applied Physics B: Lasers and Optics 100(1), 61-76, 2010

8075-29, Session 7

Exploring the betatron radiation physics using colliding pulse injection

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Betatron X-ray radiation in laser-plasma accelerators is produced when electrons are accelerated and wiggled in a laser-wakefield cavity1,2. The properties of this radiation strongly depends on the electron beam parameters and the focusing channel. We will demonstrate the possibility to produce a stable laser-produced Betatron X-ray beam with a controlled spectrum and divergence. This can be achieved by using the colliding pulse injection scheme where electrons are trapped during the collision of two laser pulses. This scheme allows to produce stable (100% reproducibility) and high-quality (mono-energetic) electron beams, with an energy tunable by changing the collision position3. We will present experimental results on the simultaneous characterization of the electron and X-ray beams in the regime of colliding pulse injection performed with a collision angle of 135 degrees. The results show for the first time a clear and unambiguous correlation between the X-ray spectra, the X-ray beam divergence and the electron energy, confirming the mechanisms at the origin of the observed X-ray radiation. When the final electron energy increases,

X-rays are more energetic and more collimated.

Finally, we will present recent results on Betatron X-ray production in capillaries, which are used either as a steady-state-flow gas cell4 or as a waveguide with an electrical discharge 5,6,7.

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8075-30, Session 8

Resonant laser plasma accelerated electrons: betatron radiation from gamma-ray to laser harmonic generation

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Betatron radiation emitted by electrons accelerated in a laser plasma wakefield accelerator is a promising bright ultra-compact light source. The presence of the electromagnetic field of the laser in the accelerator can dramatically change the electron motion and lead to a resonance in the electron motion. We studied the radiation properties in the non resonant, weakly resonant and strongly resonant regimes. The spatial and temporal coherence properties of the source are investigate experimentally, and a theoretical model is presented.

8075-31, Session 8

Relativistically oscillating plasma surfaces: high harmonic generation and ultrafast plasma surface dynamics

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High harmonic generation from intense laser solid density interactions [1] has, over the last decade, demonstrated its clear potential as a next generation source of ultrafast, coherent X-rays. Recent observations of attosecond phase locking [2] and diffraction limited performance [3] have shown that the exceptional coherence properties of the intense driving laser (>1020Wcm2) can be transferred directly to the extreme ultraviolet (XUV) and X-ray regions of the spectrum with unprecedented efficiency. This is achieved via 2 physically distinct mechanisms: a) coherent wake emission (CWE) in the bulk plasma formed up to the maximum plasma frequency of the target [4], and b) the formation of a relativistically oscillating mirror (ROM) at the critical density surface (up to 1000's of orders [5]).

When a high contrast laser pulse (i.e. contrast >109 at ~500fs for a 30fs pulse) is incident on a solid density target, a well defined critical density plasma surface is formed during the rising edge of the pulse, with a sharp density rise to solid over a distance less than the incident driving laser wavelength. Under these specific conditions the remainder of the incident laser pulse can couple directly to the critical density surface causing it to oscillate at approximately the speed of light. This effectively constitutes a oscillatory extension to Einstein's flying mirror for the relativistic Doppler effect. As described by Baeva et al using the theory of relativistic spikes [6] this mechanism permits rapid intensity scaling in the relativistic limit to very high orders (3, where   is the maximum relativistic Lorentz factor of the driving laser pulse). The formation of the smooth/well defined critical density surface for efficient ROM generation is achieved by contrast enhancing plasma mirrors which will be discussed in some detail.

One of the more intriguing results to date has been the observation of beaming of both XUV and X-ray harmonics from targets with initial surface roughness greater than that of the emitted harmonic wavelength [3, 5]. For the first time an analytic theory is presented, supported by particle in cell code simulations, to study the process via which ultrafast plasma dynamics in the relativistic regime can account for the extreme smoothing of the initial surface roughness of a solid density target. This smoothing is shown to permit the formation of a relativistically oscillating plasma surface with qualities suitable for the experimentally observed coherence properties in emitted harmonic beams, namely diffraction limited performance and attosecond phase-locking.

Finally, in a novel series of experiments, the transmission of relativistically oscillating mirror harmonics through ultra thin (nm thick foils) foils is examined. These harmonics have been used to probe the 1-D radial density profile of a preheated target, demonstrating the clear application of ROM harmonics as a broadband ultrafast XUV/X-ray density probe, suitable for the in-situ study of warm dense matter and inertial confinement fusion targets.

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8075-32, Session 8

Status of Thomson backscattering experiments at the HZDR

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The generation of ultrashort X-ray pulses via the Thomson backscattering mechanism is proposed for the study of the mechanism itself and for its later application in single-shot X-ray pump probe experiments. Here, an electron bunch with energies up to 35 MeV and charges up to 1 nC delivered by the radiation source ELBE will collide with a counter-propagating high power laser pulses (up to 3 J, 30 fs) from the DRACO Ti:Sapphire laser system. Our previous theoretical studies predicted that scattered photon energy as high as 27 keV within a picosecond pulse could be obtained in this scenario yielding a total number of X-ray photons of the order of 10^6 per pulse. The linear and nonlinear regime of the interaction can be studied by tuning the laser intensity.

8075-33, Session 8

Gamma-ray generation using laser-accelerated electron beam

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A compact gamma-ray source using laser-accelerated electron beam is being under development at KAERI for nuclear applications, such as, radiography, nuclear activation, photonuclear reaction, and so on. One of two different schemes, Bremsstrahlung radiation and Compton backscattering, may be selected depending on the required specification of photons and/or the energy of electron beams.

Compton backscattered gamma-ray source is tunable and quasi-monochromatic and requires electron beams with its energy of higher than 100 MeV to produced MeV photons. Bremsstrahlung radiation can generate high energy photons with 20 - 30 MeV electron beams, but its spectrum is continuous. As we know, laser accelerators are good for compact size due to localized shielding at the expense of low average flux, while linear RF accelerators are good for high average flux. We present the design issues for a compact gamma-ray source at KAERI, via either Bremsstrahlung radiation or Compton backscattering, using laser accelerated electron beams for the potential nuclear applications.

We use a code GEANT4 to estimate the flux and energy distribution of gamma rays as well as to predict the activation process. The dependence of the photonuclear reaction on initial parameters, like electron beam and conversion target is discussed. The preliminary experimental data are presented with the comparision of the calculated spectrum.

8075-34, Session 8

Replacing magnetic wigglers with density ripple in free-electron lasers for THz radiation

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The field of Terahertz (THz) radiation generation is of great current interest due to its potential applications in biological imaging, remote sensing, chemical and security identification. However, lack of a medium with sufficiently large dipole moment for the transition levels in the THz frequency range limits the conventional methods, used to generate radiation in optical and ultrahigh frequency range, to give high yields of THz radiation. Some of the common schemes to generate THz radiation involve interaction of femto second laser and highly energetic electron beams with plasmas. Plasma is used as a medium because it can provide a very high dipole moment and can easily handle very high power radiations. An alternative free electron laser concept for producing coherent terahertz radiation is investigated.
A weakly relativistic electron beam impinged on rippled underdense plasma, at an angle to the ripple wave vector, interacts with a seed terahertz signal to produce a space charge beam mode. The oscillatory electron velocity due to the beam mode beats with the density ripple to generate a coherent electromagnetic wave in the terahertz frequency range in forward direction. For an electron beam with 5 MW power, one can obtain ~ 40 kW power at 1 THz frequency.

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8076-01, Session 1

X-ray optics for the 2020's

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No abstract available

8076-02, Session 1

Compact optics for high resolution spectroscopy of celestial x-ray sources

W. C. Cash, Jr., Univ. of Colorado at Boulder (United States)

I will present the optical design developed for the WhimEx Explorer proposal. It features a highly compact arrangement of grazing incidence optics that generates over 300 square centimeters of effective area at resolution of 3000 to 5000 in the 0.1 to 2.0keV band. This is an order of magnitude improvement in both area and resolution over Chandra, yet still fits within an Explorer budget.

8076-03, Session 1

Extremely lightweight X-ray optics based on thin substrates

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The future large space X-ray imaging telescopes (such as IXO by ESA/NASA/JAXA) require novel, light-weight but still very precise approaches. One of the most promising possibility is the use of thin (typically 0.2-0.7 mm thick) substrates (e.g. thin float glass or Si wafers) which need to be preciely shaped mostly to Wolter geometries (parabola-hyperbola). I will present the various materials and approaches proposed and tested as well as preliminary results obtained. The quality of Si wafers was improved at the production stage and then the methods to bent them to precise geometrical surfaces were investigated including the application of stress in thin films and layers deposited on the substrates. The advantages and limits of this method will be also discussed as well as possibilities of active optics approach.

8076-04, Session 1

Deformable mirrors for X-ray astronomy and beyond

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No abstract available

8076-05, Session 1

Technologies for manufacturing of high angular resolution multilayer coated optics for the New Hard X-ray Mission

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In the frame of technology development to be used for the Optical Payload of next future X-ray missions such as New Hard X-ray Mission (NHXM), Italian project that will be operated by 2017, a new set of manufacturing techniques were finalized by Media Lario Technologies (MLT), in collaboration with Brera Astronomical Observatory (INAF/OAB) and Italian Space Agency.

The set of new technologies includes master manufacturing machines and processes, electroforming method, a vertical optical bench and metrology machines to support manufacturing and integration of mirrors. A magnetron sputtering PVD machine was upgraded and a Pt/C development study has been performed on the basis of the W/Si results obtained in the first phase of the study.

New manufacturing technologies for high accurate masters was developed and tested by mean of two full-size masters together with several dummies. A number of ultrathin Nickel-Cobalt focusing mirrors were manufactured via galvanic replication process from the masters and coated with Pt/C multilayer. Tests on substrate material, roughness and shape of the shell together with analysis on specimens were performed. Tests with AFM and XRR supported the development of the Pt/C multilayer which is the enabling technology for focusing high energy X-Rays.

Several mirror shells were integrated into two demonstrator modules to assess the whole manufacturing process up to optical payload integration. The modules were also tested at PANTER X-Ray facility to evaluate the reflectivity of the mirror shells under high energy X-Rays.

The summary of the results from manufacturing and testing of specimens and mirror shells is reported in this paper together with a description of the technologies now available at MLT.

8076-06, Session 2

X-ray imaging with Kirkpatrick-Baez optics: a review

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No abstract available

8076-07, Session 2

Innovative multilayer coatings for space solar physics: performances and stability over time

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Different solar missions are in progress and others are foreseen in the next future to study the structure and the dynamics of the Sun and its interaction with the Earth. For example, the Solar Dynamics Observatory (SDO) has been launched on February 2010 and will study how solar activity is created and how Space Weather comes from that activity. The SOLar Orbiter (SOLO) instead should be launched on January 2017 and it will be at the smallest distance from the Sun reached so far. Its general purpose is the better knowledge of the Solar System by viewing the solar atmosphere with high spatial resolution and combine this with measurements made in-situ. Different instruments devoted to solar physics are required to have high reflecting MultiLayers (ML) coatings. For example, the METIS coronagraph will fly on board of SOLO to perform simultaneous observation at 30.4 nm (He-II Lyman-α line), 121.6 nm (H-I Lyman-α line) and in the visible range, therefore its optics will require high performances in a wide spectral region. It should be desirable to reach higher reflectivity as well as long term stability and lifetime, then different proposals will be considered. SCORE is a prototype of METIS equipped with Mg/SiC optics and it has flown on board of a NASA sounding rocket. The Mg/SiC multilayers offer good performances in terms of reflectivity, but the long term stability and the lifetime have been preliminary investigated and are open problems to be further studied. As valide option we present the design and the reflectivity tests of new multilayer structures based on well known Mo/Si stack in which the performances have been improved by superimposing innovative capping layers. Besides these structures a novel couple of materials has been taken into account: the Ir/Si is an alternative to be considered. All multilayers are tuned at 30.4 nm line and the design has been optimized to maximize the performances at 121.6 nm and 500 - 650 nm visible range.

8076-08, Session 2

Performance of Kirkpatrick-Baez test modules as measured in full aperture X-ray tests

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No abstract available

8076-09, Session 2

The X-Ray optics design for the cryogenic imaging spectrometer on-board ORIGIN

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ORIGIN is a Medium size high energy mission concept submitted to ESA in response to the Cosmic Vision call issued on July 2010. The mission will investigate the evolution of the Universe by performing high energy resolution soft X-ray spectroscopic measurements of metals formed in different astrophysical environments, from the first population III stars at $z > 7$ to the present large scale structures. The main instrument on-board ORIGIN will be a large format array of TES X-ray micro-calorimeters covering a FOV of 30' at the focal plane of a 2.5 m focal length grazing incidence telescope with an angular resolution of 30" HEW. We present the telescope design which is based on hybrid technologies, namely Silicon Pore Optics for the outer section and Ni electro-forming for the inner section; we present the expected performances based on test measurements and ray-tracing simulations and we describe the main technical criticality of the telescope concept.

8076-10, Session 2

Optical subsystems characterization in laboratory

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Probing of Hermean Exosphere by Ultraviolet Spectroscopy (PHEBUS) is a dual spectrometer working in 55 - 155 nm Extreme UltraViolet (EUV) and 145 - 315 Far UltraViolet (FUV) spectral ranges. It will fly on board of the Bepi Colombo mission to analyze the composition and the dynamics of the Mercury exosphere. The characterization of optical subsystems is a fundamental task in the instrument calibration activity. The subsystem optical components can be fully described by the associated Muller Matrix. Philosophy, capabilities and the limits of a laboratory experimental approach is presented. Results and future planned activities on Phebus optical subsystems are also reported.

8076-11, Session 2

Preliminary imaging tests of lobster eye optics for nano-satellite

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The grazing incidence X-ray optics called lobster eye provides wide field of view of the order of many degrees, for this reason it seems to be a convenient approach for the construction of future all-sky X-ray monitors. The prototype lobster eye module optics of focal length of 250mm manufactured in Rigaku Innovative Technologies Europe, s.r.o. (Czech Republic) is presented.

Small mass and dimensions of this module allows it to be boarded on a nano-satellite. The performances of this lobster eye have been experimentally tested in quasi parallel beam full imaging mode using the 35 meters long X-ray beam-line of INAF-OAPA in Palermo (Italy). The X-ray images at the focal plane have been taken with a MCP detector at several energy values from 0.3 keV to 8 keV. The gain, the field of view and the angular resolution have been measured. Preliminary results are presented. Experimental results are compared to the results of the simulations.

8076-25, Poster Session

Performance benchmark of a gateable micro-channel plate detector for extreme ultraviolet radiation with high temporal resolution

J. Hauck, R. Freiberger, L. Juschkin, RWTH Aachen (Germany)

Research in ultrafast nanoscale phenomena requires high spatial and temporal resolution detectors. Optical imaging microscopes achieve high time resolution but low spatial resolution and scanning

microscopes vice versa. Extreme ultraviolet imaging microscopy closes this gap but demands a suited two dimensional detector for efficient use of photons and simultaneously enabling fast gating.

We use a micro-channel plate photoelectron multiplier together with a phosphor screen as detector. A channel spacing of 3 microns leads to a state-of-the-art spatial resolution.

We pulse the operation voltage of the electron-multiplier during 1 ns.

Only during that time the detector is highly sensitive to extreme ultraviolet light.

We analyzed the following performances of the detector system:

- Temporal behavior is measured by femtosecond illumination with a high harmonic generation laser at different relative delays.

- Spatial resolution is determined by mapping the shadow of a sharp edge on the detector. The smearing gives information about the modulation transfer function. It could be shown that single channels are visible.

- Spectral sensitivity of the detector is calibrated for extreme ultraviolet wavelengths ranging from 1 nm to 30 nm at the Physikalisch-Technische Bundesanstalt facility at the BESSY synchrotron in Berlin.

In summary the detector leads to resolutions below 50 nm and shorter than 1 ns using a discharge produced plasma EUV source and a zone plate based microscope with a moderate magnification of ~ 250x. This is a highly interesting combination and will help understanding short time nanophysics in laboratory usage.

8076-26, Poster Session

The CODEX sounding rocket payload

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We present the CODEX sounding rocket payload, a soft x-ray (0.1-0.7 keV) spectrometer with a 3.25x3.25 degree field of view. The payload is the third-generation version of the CyXESS and EXOS payloads from the University of Colorado, incorporating large-format gaseous electron multiplier (GEM) detectors and off-plane reflection gratings to achieve diffuse-source spectroscopy with a resolution of ~100. The CODEX payload has a larger bandpass, higher throughput, and a more robust mechanical structure than its predecessors. We will discuss the upgrades we made to the experiment for the third flight. CODEX is scheduled to target the Vela supernova remnant with an early 2011 launch; we may present new flight data.

8076-27, Poster Session

CODEX sounding rocket wire grid collimator design

A. F. Shipley, B. Zeiger, T. Rogers, Univ. of Colorado at Boulder (United States)

CODEX is a sounding rocket payload designed to operate in the soft x-ray regime. The instrument has a 3.25 degree square field of view that uses a one meter long wire grid collimator to create a beam that converges to a line in the focal plane. Wire grid collimator performance is directly correlated to the geometric accuracy of actual grid features and relative locations. Manufacturing and assembly techniques are strategically combined in this design that is engineered for precision within the confines of a typical rocket budget. Expected resilience of the collimator under flight conditions is predicted by mechanical analysis.

8076-28, Poster Session

Optimization of the MARS-XRD collimator using converging blades

C. Pelliciari, L. Marinangeli, F. Critani, A. Baliva, International Research School of Planetary Sciences (Italy) and Univ. d'Annunzio di Pescara (Italy); I. Hutchinson, Space Research Centre (United Kingdom)

Mars-XRD is an X-ray diffractometer developed for the in situ mineralogical analysis of the Martian soil and it is a part of the payload of the ESA ExoMars mission. The main components of the Mars-XRD experiment are: a Fe55 radioactive source, a collimator and a CCD-based detector system. For spectroscopic requirements, the beam section should not be larger then 0.5 x 10 mm2 at sample distance.

The current collimator baseline is based on a two-windows system that uses about 20% of the total source emitting surface.

To improve the X-ray flux, we are studying a collimator with converging blades which permits to use the entire source emission and tune the beam section.

In order to better estimate the efficiency of this new collimator and because of the high number of variables, a C++ program has been written that look for the best blades configuration among billion of combinations. In addition to the collimator configuration, this software simulator gives the sample photons distribution for different angles of the tilt of the source and for each couple of blades.

The optimized collimator transmits a flux 30% higher than a system with converging blades with the same aperture each and 5 times higher than a two windows collimator. Moreover the target photon distribution is a triangle function well focused on the sample surface instead of an irregular function obtained with the previous system.

Higher performances arise with the source perpendicular to the source-sample direction. Tilting the source of 40 degrees the flux became 10% weaker but the angular resolution increase of 20%.

Thanks to this optimization we expect to strongly improve the resolution of the diffraction pattern which is the main goal of the current activities of the instrument development.

This software simulator could be used also for the optimization of collimator system for the other wavelength and applications (e.g. radiotherapy).

8076-29, Poster Session

Focusing EUV radiation from the capillary discharge source on PMMA layer

V. Pickova, Czech Technical Univ. in Prague (Czech Republic)

Capillary discharge source has been constructed at the Czech Technical University in order to study the discharge as an extreme ultraviolet (EUV) source for scientific and industrial applications. Rotationally symmetric ellipsoidal mirror was used in off-axis geometry in order to focus small diameter EUV beam. Diameter in focal spot is 263 m. We used the focused radiation to obtain the craters in the PMMA layer.

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8076-12, Session 3

Multilayer coatings for the far- and extreme ultraviolet

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The far and extreme ultraviolet (FUV: 105-200 nm, EUV: 10-105 nm)

ranges are demanding better coatings to face challenging applications in various fields such as instrumentation for astronomy, solar physics, lithography, high harmonic generation, spectroscopy, etc. The performance of the available coatings is limited by the fact that all materials in the EUV, and most materials in the FUV, absorb radiation.

Absorption of materials in nature becomes a major difficulty for the preparation of efficient EUV-FUV coatings in the ~50-120 nm range. The latter range most often makes use of single-layer coatings (sometimes coated with a protective layer) because little radiation penetrates deeper. This limits the performance of the coating and it has impeded the development of narrowband coatings so far. Above 120 nm, some materials (fluorides) start to exhibit low absorption, and this enables the development of coatings with higher performance.

GOLD's efforts are devoted to develop novel coatings with improved performance in the difficult spectral range of 50-120 nm and longwards up to ~200 nm. Recent upgrades of our laboratories result in the capability to deposit coatings and to measure their EUV-FUV characteristics in clean-room conditions:

1) An existing reflectometer-deposition system has been placed in an ISO-8 clean room. This instrument enables the deposition of multilayer coatings by evaporation and ion-beam-sputtering in ultra high vacuum (UHV), and their characterization in situ in the 12-200 nm range.

2) A new deposition chamber is under development and it will be placed in an ISO-6 clean room. The chamber has an internal diameter of 75 cm and it will be devoted to multilayer deposition by evaporation.

Our recent developments include:

a) Novel broadband coatings, with enhanced reflectance at wavelength longer than 50 nm. They are based on an Al/MgF_2/SiC multilayer

b) Novel narrowband coatings peaked at wavelengths within the ~50-100 nm range. They are based on lanthanide materials, along with Al and SiO.

A summary of our recent research and of new research underway towards the development of reflection-rejection coatings and polarizers for the spectral range 100-122 nm will be presented.

8076-13, Session 3

Small diameter multilayer coated x-ray concentrators

P. Hoghoj, Xenocs (France)

No abstract available

8076-14, Session 3

Multi-layer coated Echelle grating for x-ray phase-contrast imaging

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Transmission grating-based x-ray interferometers have been developed into imaging devices that are sensitive to x-ray phase delays and scattering in the sample. They can potentially dramatically enhance contrasts between different types of soft tissues when compared with current diagnostic x-ray modalities. The key to reaching this goal is high density gratings, since the sensitivity to wave-front disturbance is inversely proportional to the grating period. Current grating designs consist of periodic walls etched in a silicon wafer or a polymer substrate. The incident x-ray beam is perpendicular to the wafer surface, and the transmitted x-rays are modulated by the difference between the material of the walls and in the trenches between the walls. For hard x-rays, the height of the walls needs to be large enough to give the desired amount of phase or amplitude modulation. This design has allowed grating periods near 2 microns, but smaller periods become highly difficult due to the prohibitively high aspect ratios of the walls.

To achieve higher phase-contrast sensitivity it is necessary to go beyond this limit. As a solution we propose a grating design inspired by blazed gratings coated with reflective multi-layers for EUV spectrometers. In our design of transmission gratings, multiple layers are deposited on one side of the stairs of an echelle grating substrate. The layers alternate between two materials of different indexes of refraction or absorption coefficients. The layer thickness d = (stair height)/2N, where 2N is the total number of layers. The incident x-ray beam is perpendicular to the grating lines and parallel to the planes of the layers, such that x-rays illuminate the stack of layers from the side and traverse the entire width of the layers. The width layer is the width of the stair of the echelle grating. It is designed in conjunction with the two materials of the layers to give the desired phase delay or absorption to the transmitted x-rays. In effect, each stair of the echelle substrate holds a sub-grating of N periods, and this sub-grating is repeated over all stairs. The effective grating period of this design is twice the thickness of individual layers. Since the layer thickness can be as small as tens of nanometers, as has been realized in the reflective multilayer blazed gratings for EUV, the achievable grating density of this design can be much greater than current limits.

Another consideration is that the x-ray beam exits the back surface of the echelle substrate at an oblique angle, which introduces a linearly varying phase shift across each sub-grating. An effective correction of this effect is to etch a complementary echelle grating on the back surface of the substrate.

We demonstrate this idea in an echelle grating fabricated with anisotropic etching of a (100) silicon wafer. The grating grooves are symmetric, with 54.735° blaze angle and 10 micron period. The corresponding height of the stairs is 8.165 microns. Interference fringes from the grating were characterized with a synchrotron source at APS of Argonne National Laboratory, USA.

8076-15, Session 3

Experimental investigations of backward transition radiation characteristics in extreme ultraviolet region

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Forward transition radiation in X-ray range and backward transition radiation (BTR) in optical spectral region are investigated in details due to their use for purposes of particle and beam diagnostics.

In order to improve electron beam diagnostics for new X-FEL projects we proposed to use BTR in extreme ultraviolet (EUV) region [1,2].

We performed experimental investigations of BTR characteristics in EUV spectral region generated by the 50 nm molybdenum target on silicon layer at 855 MeV electron beam of MAMI-B microtron (Mainz, Germany). Angular patterns and intensities of BTR both in optical and in EUV regions have been investigated in two different geometries using a CCD-camera sensitive in a photon energy range 1 eV - 10 keV. It is well known that BTR is generated in a wide spectral region. In order to select EUV region photons we used 1.3um aluminum foil as a filter. In order to obtain optical radiation without EUV part we used fused silica filter and blue optical filter. The measured intensity of optical BTR is twice lower than the theory predicted. The measured intensity in EUV region is significantly higher than theoretically predicted one. Our experimental estimation of the experimental BTR yield in EUV region is (2.4 - 3.6)*10^4 photons/electron and this value is more than 4 - 6 times higher than theoretical one. The theoretical model that takes into account BTR generation on a single facet of the target and does not take into account the Mo layer thickness may cause such difference.

Anyway, high BTR yield is promising for diagnostics purposes and as a next step we plan to focus obtained EUV radiation using a concave multilayer mirror.

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8076-16, Session 4

X-ray transfocators: tunable devices based on refractive optics

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Since their development almost 15 years ago, the use of X-Ray refractive lenses has rapidly expanded and they are now in common use on synchrotron beamlines. Compared to other focusing elements, refractive lenses as in-line optics are simple to align and are more stable with respect to angular vibrations in comparison to reflective optics. They can be adapted to very high X-ray energies by modifying their composition and number, and can be inserted and removed from the beam to allow fast switching of the beam size. Recently, transfocators - systems with a tuneable number of lenses have been proposed to provide permanent energy and focal length tunability. The transfocators are comprised of several cartridges containing different numbers of lenses, such that the focal distance can be continuously adjusted by insertion or retraction of one or more of the lens cartridges. There are 2 types of transfocators: in-air transfocator (IAT) and in-vacuum transfocators has been in operation at the ESRF for almost 5 years. The IVTs are water cooled to allow use in the white beam, they are installed closer to the X-ray source (~30 m) where they capture a larger proportion of the diverging X-ray beam. The variable focal length of the transfocator focused beam means that it can be exploited at all of the beamline experimental stations leading to enormous flux gains (up to 105) with respect to an unfocused beam. The transfocators are very flexible, and has been used in several different configurations, either as a standalone focusing device in the monochromatic beam, giving micrometer spot sizes. Also the transfocators can act as pre-focusing devices to be used in conjunction with a downstream micro- or nano-focusing element. Finally, without any other optics, the IVT acts as a longitudinally dispersive monochromator, producing beams with about 1% band pass and several micrometers vertical size. At the focal point, this leads to a 2 order of magnitude increase in the flux at this selected energy with respect to the rest of the spectrum. The band pass of this monochromator is well matched to exploit the spectrum of the harmonic peaks of an undulator insertion device at a third generation storage ring.

8076-17, Session 4

X-ray refractive large aperture rolled prism lenses as condensers for X-ray tubes

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At the Institute for Microstructure Technology (IMT) at Karlsruhe Institute of Technology (KIT) X-ray refractive line focus lenses are built by aligning a large number of concave and parabolic lens elements made out of SU-8 one after another. To form a point focus two of these lens stacks, tilted by 90° with respect to each other, need to be consecutively placed in the optical path. If no lenses for high-quality imaging are required the principle of Fresnel lenses can be applied to raise optical effectiveness. Such lenses provide higher ratios of refractive power to absorption. For large apertures, these lenses also have to be fabricated by means of a high aspect ratio process and again have to be tilted by 90° to each other when a point focus is required. At IMT a new fabrication method for refractive large aperture rolled lenses has been developed. These lenses are fabricated through structuring polyimide films with triangular shaped fins, cutting them in a calculated form and winding them to a spiral shape. The lenses provide the advantage of Fresnel lenses, can be fabricated in a simple way and also provide a point focus through their approximate rotational symmetry. The FWHM of such lenses is determined by the height of the triangular fins. This optics are well suited to be used as condenser lenses. At the moment the production process of the lenses is revised. Current films provide higher prism densities as well as higher optical quality for the rolled lenses. The revised lenses were also tested at an X-ray tube at Bruker AXS.

8076-18, Session 4

High-resolution X-ray microscopy for mesoscopic photonic crystals

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We developed a high-resolution x-ray microscopy (HRXRM), combining full-field imaging with x-ray diffraction, which was applied for the volume-specific studies of mesoscopic photonic crystals. Methodologically proposed approach is similar to the studies of “traditional” crystals by high resolution transmission electron microscopy (HRTEM). HRXRM was realized by employing X-ray refractive optics. The immediate benefit of using compound parabolic refractive lenses is the possibility to retrieve the high resolution diffraction pattern and real-space images in the same experimental setup.

The HRTXM was realized at the Micro-Optics Test Bench of ID06 BL with an x-ray energy from 10 to 20 keV. It consists of two sets of condensers - used for sample illumination in an imaging mode and for a high resolution diffraction mode as a Fourier transformer , the objective lens and two (large area and high resolution)X-ray CCD detectors. The tunable objective lens provides the magnification between 10 and 25. At the maximum magnification the resolution of ~100 nm was achieved. The HRXRM technique was used for structural characterization of natural and artificial opals, and inverted photonic crystals.

The proposed approach provides the tools for the efficient studies of real structure of mesoscopic materials. A number of HRTEM approaches can be directly transferred to the domain of x-rays. Among the immediate practical applications is the utility of real structure knowledge for the photonic crystal growth technology.

8076-19, Session 5

Time resolved EUV pump-probe microscopy of fs-LASER induced nanostructure formation

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We report on our efforts on setting up and building a compact Extreme Ultraviolet (EUV)-pump-probe microscope. The goal is the observation of femtosecond (fs)-laser induced nanostructure formation. The unique interaction processes induced by fs-laser radiation open up new markets in laser material processing and are therefore matter of actual research. “Sub 100 nm”-structures offer vast potential benefits in photonics, biotechnology, tribological surface design, plasmonic applications and production of nanoparticles.

Focused fs-laser radiation causes a local modification resulting in nanostructures of high precision and reproducibility. However the formation dynamics is not well understood. Research in this field requires high temporal and spatial resolution. A combination of fs-laser and EUV-microscope provides a tool for “in situ”-observation of the formation dynamics. As exemplary structures to be investigated, we use nanojets on thin gold films and periodic surface structures (ripples) on dielectrics. In the future, the EUV-pump-probe microscope can become a versatile tool to observe physical or biological processes.

Microscopy using EUV-light is capable of detecting structures on a scale down to several tens of nanometers. For detailed investigations a compact EUV-microscope has been realized utilizing OVI Balmer-alpha radiation at 17.3 nm coming from a discharge produced oxygen plasma. As optical elements a grazing incidence elliptical collector and a zone plate with a width of outermost zone of 50 nm and a spectral filter to avoid chromatic aberrations are used. The detector is a fast gated microchannel plate with a pore size of 2 microns contacted by a low impedance transmission line, so that we expect resolutions smaller than 100 nm and better than 1 ns. The newly developed EUV-microscope is a powerful tool for a wide field of investigations that need high time and spatial resolutions.

8076-20, Session 5

Measurment of characteristics XUV capillary laser

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This work concers in measurment of characteristics XUV argon capillary laser, which was developed on Czech Technical University in Prague, Faculty for Nuclear Sciences and Physical Engineering. This laser generates at 46,9 nm in Ne - like Ar. We realized Young's double slit experiment to estimate spatial coherence of this laser system and detected beam profile. We used double slits drilled on Ti:saphire laser with four distances between slits. Distances between slits were 50 um, 60 um, 100 um and 150 um. Apertures had oval shape with diameter 20 - 25 um. Interference structure we detected by CCD with resolution 512x512 pixels. This work contains also short overview about sources of XUV radiation.

8076-21, Session 5

The problem of roughness detection for supersmooth surfaces

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Nowadays the requirements for x-ray optical elements surface quality are quite high. Their achieves 0.1-0.3 nm roughness (r.m.s.) in spectrum range from E-3 to E3 inverted mcm for DUV and EUV lithography, x-ray microscopy purposes. Although, there are plenty of publications on how correctly specify and characterize the substrate surface for multilayer coatings by different methods, the question is still on the agenda. Several standard methods like x-ray diffuse scattering and specular reflection, atomic force (AFM) and optical interferometric microscopy (OIM) have been developed for this purpose, but it's also well known fact, that they often give different results in surface characterization. The goal of the substrate attestation procedure is to choose the sample for deposition the multilayer coating with better reflection properties. That's why it's really important to understand the physical causes of difference in characterizing result given by various methods and to find the most adequate one.

All methods under discussion have obvious features, making it hard or even impossible to apply them for attestation supersmooth substrates for EUV-lithography or microscopy, especially curved ones. The main OIM difficulty is using etalons, leading to doubtful measurement answer. The situation here is quite a paradoxe, because for lower spatial frequencies (E-6 to E-3 inverted mcm) it is generally known, that the result of using etalon surfaces is image distortion, that's why for precise experiments non-etalon interferometers are used.

Nowadays AFM is claimed to be the most simple and physically clear method to surface attestation. But the data treatment, especially polynomial deduction still raise questions: depending on the polynomial order, the power spectral density (PSD) curve can change dramatically. Its' also impossible to use commercial AFM devices to analyze an aspherical surface with entrance angle 10 to 20 degrees. The same problem we phase for x-ray diffuse scattering with wavelength near 0,1 nm.

Except discussion the standard methods abilities and limitation in this work we also propose a new universal device, based on both «soft» x-ray and light diffuse scattering, which seems to be physically clear, self-consistent and can also be used for surface investigation in all the spectrum range under consideration without restrict limitation for the surface shape (plane or curved ones).

8076-22, Session 5

Multilayers for next generation EUVL at 6.x nm

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Even as EUVL is approaching its first HVM phase, one can observe an increasing interest to the next generation EUVL. This is explained by the necessity to see a clear path following Moore's Law for a better spatial resolution by using EUVL technology. What would be the next wavelength depends on two major components of the steppers: source and optics. The current 13.5nm was chosen due to the existence a multilayer structure with a reasonably high reflectivity at this wavelength. By using the same criteria, the most promising wavelength for the next generation EUVL is in vicinity of 6.7nm. Lanthanum and boron based multilayer structures have a calculated reflectivity of above 70%, the same reflectivity level as demonstrated by Mo/Si pair at 13.5nm. First normal incidence La/B4C multilayers were deposited at RIT in December 2000; reflectivity as measured by CXRO was 44.3% at ~6.7nm [1]. In this paper we will present recent results on deposition, reflectivity, internal stress and temporal and thermal stability of the La/B4C multilayers. Normal incidence reflectivity of these structures at 6.67nm was measured to be 48.9% with fwhm of 0.045nm. We will also report experimental results with multilayers based on new materials combination.

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8076-23, Session 5

Freestanding multilayer films for application as phase retarders and spectral purity filters in the soft X-ray and EUV ranges

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A technique for fabrication of freestanding multilayers which are able to be used as optical elements in the soft X-ray and EUV ranges was developed. The technique provides high resonant reflectivity of multilayer films so that they are prospective as transmission type polarizers and phase retarders for the purpose of radiation polarimetry. On the other hand, freestanding multilayers exceed foils and monolayer films in mechanical strength. It gives an opportunity to manufacture film spectral filters of augmented reliability.

The majority of fabricated phase retarders were designed for a spectral region of "water window" (l = 2 - 4.5 nm). The functionality of samples was tested using synchrotron sources of radiation. It was experimentally demonstrated that freestanding Cr/Sc multilayer may serve as a quarter-wave plate close to the Sc L-edge of absorption (l = 3.11 nm). Cr/Sc structure with a period d = 3.1 nm and a number of periods N=300 provides the phase shift between s- and p-polarizations of 90° at equal transparencies of these polarizations of 0.4%. This pair of material is effective near Cr L-edge (l = 2.16 nm) as well. The samples of Cr/C and Cr/Sc phase retarders were designed for polarimetry near the carbon K-edge (l = 4.37 nm). The potentiality to fabricate freestanding multilayer phase retarders with ultra-short periods (d < 2 nm) has also been studied. Multilayers on the basis of the pairs of materials V/B4C and W/B4C with the period d = 1.7 nm (the number of periods N = 280) and d = 1.4 nm (N = 350) respectively have been fabricated.

Developed technique for fabrication of thin multilayer films has been involved to manufacture the set of freestanding filters Cr/Sc, Mo/C, Zr/Si, Zr/Al with spectral windows within 2.2 to 22 nm wavelength range. The filters are generally intended for studies of plasma EUV and soft X-ray sources. We have also fabricated Al/Si structures with supported mesh, which are transparent in the range l = 17 - 60 nm, for application

in sun astronomy.

The special attention was paid to the development of spectral purity filters for the high throughput tools of projection EUV lithography with a wavelength of operation. The comparison testing of heat load withstandability was fulfilled for a variety of freestanding multilayers consisting of Si, Zr, Mo and silicides of both metals. The method of secondary ion mass spectroscopy and measurements of optical characteristics were used to analyze temperature stimulated changes in film samples. It was found that Mo/ZrSi2 freestanding structure is more preferable for use under conditions of intensive radiation heating. The tested sample of Mo/ZrSi2 multilayer film remained undamaged after 20 hours of vacuum heating to 930ºC. The transparency at l = 13 nm decreased from 70.5% to 68.5%. The sample of Mo/ZrSi2 freestanding film 160 mm in diameter with transparency of 70% (l = 13 nm) was fabricated for the prototype of the industrial tool of EUV lithography.

8076-24, Session 5

Manufacturing and characterization of diffraction quality normal incidence optics for the XEUV range

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Due to recent advantages in making of short-period multilayer mirrors a real opportunity of imaging with nanometer-scale space resolution in the XEUV range is appeared. Such optics is essential for the tasks of projection XEUV lithography, microscopy in the “water” and “carbon” windows and the solar astronomy (λ=3-40 nm). Those are the main reasons why at present a stable interest to the problem of manufacturing of optical elements with a shape precision of reflecting surfaces at sub-nanometer scale is observed. Tradition approaches for manufacturing and surface shape characterization do not meet the requirements. The paper reports about new methods and technologies of measurement and surface shape correction developed in IPM RAS. In particular some physical aspects limiting measurement precision of the traditional pin-hole based diffraction interferometers are considered. An original point diffraction interferometer utilizing a new type of a reference wave source is described. Study of the source has shown that it has the least aberrations as compared with the conventional ones. For instance it’s aberration in numerical aperture of 0.4 does not exceed 0.3 nm. Optical circuits for inspection of different types of optics are presented.

A drastic attention in the report is devoted to the surface shape correction by ion-beam etching. Special attention is paid to the dynamic of the surface roughness vs. etching depth, energy and angle of incidence of the ions to the surface under processing. Some principal results of the investigation differ of those were reported in papers of other authors. The reason of the discrepancy is advanced methods of surface roughness measurement we used in this study.

Last experimental results in manufacturing and surface shape studies of spherical and aspherical mirrors and objectives for X-ray optics obtained in IPM are presented.

Conference 8077: Damage to VUV, EUV, and X-ray Optics (XDam3)

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8077-01, Session 1

Lifetime and damage threshold properties of reflective x-ray coatings for the LCLS free electron laser

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The Linac Coherent Light Source (LCLS) x-ray free electron laser (FEL) has been operational since 2009 at the SLAC National Accelerator Laboratory in California. This first-of-a-kind x-ray source produces ~100 femtosecond monochromatic x-ray pulses of unprecedented brightness (about 10 orders of magnitude higher than current 3rd generation synchrotron sources) in the first harmonic ranging between 0.8 and 8 keV. The revolutionary capabilities of the LCLS will generate a wealth of new research in the fields of physics, biology and materials science. The uniquely high instantaneous dose of the LCLS beam led to x-ray mirror designs consisting of an especially modified reflective coating (boron carbide or silicon carbide) deposited on a silicon substrate. Furthermore, the coherence preservation requirements for these mirrors result in very stringent surface figure and finish specifications. We have demonstrated working LCLS x-ray mirrors with coating thickness errors < 0.35 nm rms and overall figure errors ~ 2.5 nm rms across 385-mm-long clear apertures after mounting and installation were completed. Some of the LCLS mirrors start showing signs of degradation exhibited as carbon-based deposits on top of the coating surface. The main challenge in removing such contamination and restoring the mirror performance is that carbon is the main constituent of both the contaminated regions and the carbide coatings. Experimental results from techniques aiming in extending the lifetime of the LCLS x-ray mirrors will be discussed. Experimentally determined damage thresholds for the LCLS reflective coatings will also be presented and compared with theoretical models.

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8077-02, Session 1

Damage investigations for the European XFEL beamlines components

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Linear accelerator based lasers, so called Free Electron Lasers (FEL) are now becoming a reality as 4th generation x-ray light sources. Based on the SASE (Self Amplified Spontaneous Emission) process, they deliver ultra-short coherent light in the x-ray photon energy range. After the first successful development of FEL in the soft x-ray region at FLASH (Free electron LASer in Hamburg), several x-ray facilities are under construction (European XFEL in Hamburg, XFEL/SPRING8 in Japan) or recently started (LCLS in Stanford).

A brief overview of the European XFEL under construction in Hamburg will be given. Starting from 2015, it will deliver ultrashort (100 fs) pulses of x-rays ranging from 0.2 to 12.4 keV with up to 1014 photons/pulse. The scientific activity will be driven by six different experimental stations, each devoted to a specific field ranging from the study of high energy density matter to single bio-molecule imaging.

An emphasis will be given on the development of the beamline systems. In fact some experiments foreseen rely on the high photon flux or coherence properties of the beam. In this photon energy range any degradation of the beamline components might disable to perform these experiments. We will describe the on-going program which aims to determine the damage thresholds of materials, mainly carbon based, in the x-ray photon energy range. Results of recent experiments performed at LCLS, as well as theoretical development will be presented. These studies of primordial technological importance for the development of the beamlines, also address more fundamental aspects by exploring and modelling the interaction of intense x-ray pulses with matter.

8077-03, Session 1

Probing matter under extreme conditions at Fermi@Elettra: the TIMEX beamline

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Novel possibilities for studying matter under extreme conditions are opened by the forthcoming availability of free electron laser (FEL) facilities generating subpicosecond photon pulses of high intensity in the VUV and X-ray range, which are able to heat thin samples up to the warm dense matter (WDM) regime. Pump-and-probe ultrafast techniques can be used to study the dynamics of phase transitions and characterize the states under extreme and metastable conditions. Ultrafast (10-100 fs) bulk heating is seen as a novel route for accessing extremely high temperature regimes as well as the the transition region between low-density and high density fluids, that is presently considered a no man's land in simple liquids and glasses. Here we briefly describe the present status of the TIMEX end-station [1-3] devoted to those experimental activities at the Fermi@Elettra FEL facility, and preliminary results obtained in pilot ultrafast experiments. [1] Damage thresholds and effects associated with irradiation with intense pulses on surface and bulk-like targets will be briefly discussed.

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8077-04, Session 2

Soft x-ray laser driven ion acceleration and ablation in solids: niobium, vanadium and their deuterides

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Extremely intense and ultra-short soft X-ray pulses from the FLASH Free-electron Laser in Hamburg were focused to produce sufficiently high energy densities to study materials under extreme conditions (MEC). These conditions are the focus of interest for a wide range of disciplines, from structural biology to fusion, as any sample subjected to a tightly focused FLASH pulse will rapidly turn into plasma.

Here we describe results with a new sub-micron focusing optic, where power densities exceeding 10^17 W/cm^2 could be reached with 20 fs soft X-ray pulses. We report the interaction of such pulses with solids, including niobium, vanadium and their deuterides. The interaction was characterized by time-of-flight ion spectrometry and by an off-line analysis of the ensuing craters on the sample surfaces. The results were modelled, using a non-local thermodynamic equilibrium code with radiation transfer, complemented with a self-similar isothermal fluid model for plasma expansion into vacuum.

The results show saturation in the ablation process at power densities exceeding 10^16 W/cm^2. This effect can be linked to a transiently-induced X-ray transparency in the solid by the femtosecond X-ray pulse at high power densities. Furthermore, protons and deuterons with kinetic energies of several keV have been measured, and these concur with predictions from plasma expansion models.

Our results show a clear correlation between the energy density on the sample surface and the number and energy of ions ejected during crater formation. The correlation can be used to find the focus, which is not a trivial task by conventional methods when using sub-micron focusing. Combined with the information about beam intensity, an ion time-of-flight spectrometer provides sensitive indication about the power density on the sample.

8077-05, Session 2

Transversal and longitudinal non-Gaussian laser beam characterization by ablative imprints in various solids

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During the last decade, the soft X-ray and X-ray lasers demonstrated their unprecedented capabilities on the field of basic laser-matter interaction research. Several new, especially linac-based, X-ray laser sources have been put into the operation and are currently in use. A correct utilization of such sources, however, requires a rigorous knowledge of the output laser beam parameters. Our efforts aim at the characterization of the spatial fluence distribution, whether it be in transverse or longitudinal direction, respectively. In this contribution, we summarize our recent achievements on the field of X-ray laser beam characterization. Our methods are based on the ablative imprints in various solid state materials, e.g., poly(methyl methacrylate) (PMMA), amorphous carbon (a-C), and lead tungstate ($PbWO_4$). Owing to the increased wavefront distortions, the X-ray laser beams cannot be treated in a standard Gaussian approach. Therefore, new techniques of non-Gaussian laser beam characterization have to be developed. Methods of transverse beam profile reconstruction, fluence scan (F-scan), and longitudinal beam characterization (z-scan) are the main subjects of this work.

8077-06, Session 3

Ablation of solids using an extreme ultraviolet free electron laser at SCSS test accelerator

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A focusing mirror system at the extreme ultraviolet (EUV) beamline of the SPring-8 Compact SASE Source (SCSS) has developed. The horizontal and vertical sizes of the beam at the focal point were measured to be 16 μm and 13 μm at a wavelength of 60 nm. A high power density over 100 TW/cm2 was achieved. Ablation properties of some materials such as silicon, diamond and tantalum have been studied for determining the focused beam profile with a single shot irradiation.

8077-07, Session 3

Damage in Mo/Si multilayer optics irradiated by intense short-wavelength FELs

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Multilayer coated optics are used for control of XUV (eXtreme-UltraViolet) and soft X-ray radiation in many fields of science and technology, and the development has experienced a considerable boost by the application in advanced photolithography. A new field

is the application in experiments at short wavelength Free Electron Lasers. This includes FLASH (Free electron LASer in Hamburg, Germany) and LCLS (Linear Collider Light Source in Stanford, USA) sources, operating in two spectral regimes: XUV and soft X-ray, respectively. Multilayer coated optics are most promising candidates for optical schemes at such sources, fulfilling extreme requirements in terms of figure and roughness errors, wavefront preservation, and stability, especially under near normal incidence conditions. However, the photon flux from short wavelength Free Electron Lasers is extremely high. Damage of the optics can be expected (even after a single shot exposure) what can limit the performance of the multilayer optics. Thus radiation resistivity of optical coatings must be studied.

The results of the damage studies of the Mo/Si multilayer coating (broadly used in lithography applications) with femtosecond XUV radiation at FLASH facility were presented previously [1]. Melting of the silicon layers, followed by molybdenum atoms diffusion into the liquid volume and consequently silicide-formation was found as the leading mechanism for irreversible structural changes for fluences at and just above the damage threshold. We have extended our research on the flux resistivity of Mo/Si multilayers to a wavelength in the soft X-ray part of the spectrum. Samples were irradiated at LCLS free electron laser at different intensity levels with single shots. The permanent damage of surfaces was investigated by means of phase-contrast microscopy, atomic force microscopy, and transmission electron microscopy. Observed morphological and structural changes of the material were used to determine the damage mechanism. Although the final state of the damage is very similar to the case of the FLASH irradiation, the damage threshold appeared to be strongly wavelength dependent and the deposited energy density at the damage threshold much lower. A possible explanation will be discussed during the presentation. The results are important for the design and further development of the optical coatings for the new generation of the short wavelength light sources, not only for the multilayers but for the single metallic layer coatings as well.

[1] A. R. Khorsand et al., Opt. Express 18, 700 (2010)

8077-08, Session 3

Femtosecond laser-induced periodic surface structures: importance of transient excitation stages

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The formation of laser-induced periodic surface structures (LIPSS) upon irradiation of metals, semiconductors and dielectrics by linearly polarized high-intensity Ti:sapphire fs-laser pulses (pulse duration ~130 fs, center wavelength ~800 nm) is studied experimentally and theoretically. In the experiments, two different types of LIPSS exhibiting very different spatial periods are observed (so-called LSFL - low spatial frequency LIPSS, and HSFL - high spatial frequency LIPSS), both having a different dependence on the incident laser fluence and pulse number per spot. The experimental results are analyzed by means of a new theoretical approach, which combines the generally accepted LIPSS theory of J.E. Sipe and co-workers [Phys. Rev. B 27 (1983), 1141] with a Drude model, in order to account for transient changes of the optical properties of the irradiated materials. The joint Sipe-Drude model is capable of explaining numerous aspects of fs-LIPSS formation, i.e., the orientation of the LIPSS, their fluence dependence as well as their spatial periods [1,2].

The latter aspect is specifically demonstrated for crystalline silicon, which show experimental LSFL periods somewhat smaller than the laser wavelength. This behaviour is caused by the excitation of surface plasmon polaritons, SPP, (once the initially semiconducting material turns to a metallic state upon formation of a dense free-electron-plasma in the material) and the subsequent interference between its electrical fields with that of the incident laser beam, resulting in a spatially modulated energy deposition at the surface. Upon multi-pulse irradiation, a feedback mechanism, caused by the redshift of the resonance in a grating-assisted SPP excitation [3], is further reducing the LSFL spatial periods. The SPP-based mechanism of LSFL successfully explains the remarkably large range of LSFL periods between 60% and 100% of the laser wavelength.

In dielectric materials, experiments with double-fs-laser-pulse irradiation sequences of variable temporal pulse-to-pulse separation in the fs-ps range further confirm the importance of the transient excitation stages - associated with the formation of a dense quasi free electron plasma in the conduction band of the solid - during the early stages of LIPSS formation.

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[2] J. Bonse, A. Rosenfeld, J. Krüger, J. Appl. Phys. 106 (2009), 104910.

[3] M. Huang, F. Zhao, Y. Cheng, N. Xu, Z. Xu, ACS Nano 3 (2009), 4062.

8077-09, Session 3

Dual-action of XUV and IR femtosecond pulses in the structuring of materials surfaces

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We present a new method for efficient structuring of surfaces of materials using femtosecond NIR laser pulses simultaneously with a weak extreme ultraviolet (XUV) beam leading to very strong radiation-matter interaction bringing dramatic increase of the surface processing speed. As an example, we present results on surface nanostructuring of amorphous carbon. We present a new explanation of the mechanism of creation of laser-induced periodic surface structures (LIPSS) by means of convective currents on the surface of a non-thermally molten material.

8077-10, Session 4

Transient analysis of thermal distorsion in a silicon substrate on incidence of a single soft X-ray FEL pulse

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The analysis of thermal distortion in optical surfaces subjected to X-ray FEL pulses must address entirely new issues, as compared to the simpler case of synchrotron light produced in a storage ring. This is because the X-ray FEL pulses are shorter and the peak power density larger, by many orders of magnitude, than in a storage ring. Therefore, considerations based only on the average power absorbed by optical substrates gives a very incomplete picture of the expected optical performance.

We report first results on an on-going project to describe in detail and on a very fine time scale, the disturbance of an optical surface upon illumination with a single femtosecond, high power X-ray pulse.

Radiant energy from the X-ray pulse is initially given the electronic system (ES) in a surface layer of the substrate, whose optical functions are also expected to change in time during the incidence of the pulse. The ES next relaxes expelling photo and Auger electrons, and transferring energy to the atomic cores. The ensuing phonon distributions propagate into the colder depths of the optical substrate, while its surface becomes distorted on a surprisingly short time scale.

Our method starts from a rather general formulation of non-equilibrium hydrodynamics [1], contemplating the energy and matter densities in the material medium, and its tensor fluxes of all orders. For times t>T0 (T0 estimated here as about 200 fsec) we find it possible to truncate the infinite system of equations and solve them. T0 is a time after the optical excitation, such that for t>T0 local time-dependent functions quasi-temperature T(r,t) and density of matter n(r,t) can be defined. Suitable thermo-mechanical boundary conditions are also imposed.

The solution of the resulting pair of equations [2] then shows that, after incidence of a single typical soft X-ray FEL pulse, a silicon substrate will bulge locally at t about 200 nsec, creating a local surface figure error of circa 1 microrad. Its amplitude decays on a time scale of microseconds. If trains of femtosecond pulses spaced by a few hundred nanoseconds are contemplated, resonant enhancement of the surface bulge may increase the figure error to intolerable values.

Current work is focused on extending the applicability of this non-equilibrium hydro-dynamic approach to times shorter than T0; then additional dynamical variables are needed and a larger set of more complicated equations has to be solved.

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[2] A R B de Castro, A R Vasconcellos and R Luzzi, Rev of Sci Instrum., 81, art 073102 (2010)

8077-11, Session 4

Computer simulation of heat transfer in zone plate optics exposed to X-ray FEL radiation

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Zone plates are circular diffraction gratings that can provide diffraction-limited nano-focusing of x-ray radiation. When designing zone plates for X-ray Free Electron Laser (XFEL) sources special attention has to be made concerning the high intensity of the sources. Absorption of x-rays in the zone material can lead to significant temperature increases in a single pulse and potentially destroy the zone plate. The zone plate might also be damaged as a result of temperature build up and/or temperature fluctuations on longer time scales. In this work we simulate the heat transfer in a zone plate on a substrate as it is exposed to XFEL radiation. This is done in a Finite Element Method model where each new x-ray pulse is treated as an instantaneous heat source and the temperature evolution between pulses is calculated by solving the heat equation. We use this model to simulate different zone plate and substrate designs and source parameters. Results for both the 8 keV source at LCLS and the 12.4 keV source at the European XFEL are presented. We simulate zone plates made of high Z metals such as gold, tungsten and iridium as well as zone plates made of low Z materials such as diamond. In the case of metal zone plates we investigate the influence of substrate material by comparing silicon and diamond substrates. We also study the effect of different cooling temperatures and cooling schemes. The results give valuable indications on the temperature behavior to expect and can serve as a basis for future experimental investigations of zone plates exposed to XFEL radiation.

8077-12, Session 4

Time-resolved investigation of thermal distortions induced by a high flux x-ray beam in optical substrate

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Free-electron lasers in the x-ray regime put new demanding constraints on the design of x-ray optics to preserve the unique beam properties of these sources. Besides improved manufacturing, mounting and alignment, a better knowledge of the response to high-flux x-ray radiation is required for best in-situ performance of these optical elements. Herein we present results of a time-resolved pump-probe experiment performed at the ESRF ID09 beamline. We investigated the time behavior of an optical silicon substrate exposed to a high flux of 15 keV photons. To produce the high photon flux required, the x-ray beam is focused down to about 150µm x 50µm onto the sample. The thermal load in the optical substrate produces a thermal distortion which is probed by an infrared fs-laser, the wavefront and intensity of which is monitored using a Hartmann-Shack sensor. Nanometer wavefront deformations are detectable in the probe beam when the substrate is under radiation load. Shape and amplitude of the thermal mirror distortion is reconstructed from the measured wavefront deformation, and the time scale for building up and decaying of the distortion is computed. The experimental results are compared to finite element simulations.

8077-13, Session 4

Time-dependent study of diamond Bragg reflectivity under heat load of ultrashort laser pulse excitation

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Intense radiation pulses generated by x-ray free-electron lasers produce time-dependent heat load on x-ray optics which may affect performance of x-ray optical elements, particularly diffracting crystals.

To evaluate the influence of instantaneous absorption of the radiation pulses on the crystal lattice we studied time-dependent Bragg reflectivity of diamond crystals in backscattering using highly monochromatic x-rays with millielectronvolt-narrow bandwidth.

The backscattering signal was gated to measure the reflectivity at different time intervals following ultrashort (~50 fs) laser pulse excitation with a wavelength of 400 nm, power of ~500 mW, and a repetition rate of 5 kHz.

Preliminary data analysis reveals time-dependent variation in the reflectivity curve in the time interval from 0.1 to 500 ns.

A characteristic response time of the crystal lattice to the ultrashort laser pulse was found to be a few nanoseconds.

Detailed interpretation of the obtained results is underway.

8077-14, Session 4

Time resolved optical methods for investigation of phase transformations in materials exposed to nanosecond laser pulses

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Infrared radiometry (IR) and time resolved reflectivity (TRR) methods were used for investigation of laser pulse effects on materials in nanosecond time scale. The methods in combination were capable to quantify object temperature and detect phase transformations in the solid state, melting, and plasma formation.

The experimental system is described. It contains KrF excimer laser with homogenizer and variable attenuator, fast IR detector for radiometry, continuous probing laser with Si photodiode for reflectivity measurement and ultraviolet (UV) detector for KrF laser pulse reflection measurement. The range of energy densities used was 100-5500 mJ cm-2 and measurements were done with temporal resolution of 6 ns for radiometry and 1 ns for reflectivity.

Surface temperature during Nd:YAG and KrF pulsed laser heating was measured for 14 different materials.

Melting process induced by the KrF laser pulse was identified in the IR spectra. First, the temperature increases continuously to a level much higher than the equilibrium melting temperature without any sign of a phase change. The temperature maximum is reached at the

end of the high part of the laser pulse. During the cooling a plateau of almost stable temperature (or inflection point) forms before the end of the solidification of the liquid phase, with temperature close to the equilibrium melting temperature. If the solid material changes its phase during cooling, another plateau or inflection point is observed near its transformation temperature. This behaviour was observed for all samples where the laser melting was investigated: Si, Mo, Ni, Cu, Sn, Ti, steel SN 15330 and stainless steel SN 17246 samples.

For silicon material the transient thermal emission including melting induced by the KrF laser pulse has different form than for metals. It has three peaks and a plateau and the form changes with changing energy density. It is caused by semi-transparency in solid and opacity in liquid phase.

Melting process was also identified in the time resolved reflectivity spectra. For silicon the TRR signal forms a straight and smooth plateau at approximately 73 % of reflectivity during the existence of liquid phase. When the melting occurs on the metallic surface, the TRR peak (maximum or minimum) moves to the later time than for only heating and a sharp change of the reflectivity evolution is found during the solidification.

The sample surface reflected KrF laser light temporal evolution can indicate the melting start time. It is the time when the signal including melting increases significantly from the signals induced by low energy density laser pulses.

By the combination of the three methods the melting duration and threshold were more reliably identified than by only one method. The thresholds and durations are shown for the 8 samples, mentioned above.

For the silicon sample treated by the laser irradiation of previous pulses the measured traces had several differences from the previous case at the similar laser pulse energy density. They indicate heating to higher temperatures, deeper melting and start of plasma formation.

8077-15, Session 4

Thermal analysis and proton implantation experiment to evaluate the stability of multilayer coatings in a space environment close to the sun

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The next SOLO (SOLar Orbiter) mission will carry onboard the METIS (Multi Element Telescope for Imaging and Spectroscopy) instrument which will perform broad-band and polarized imaging of the visible K-corona and narrow-band imaging of the UV (HI Ly α, 121.6 nm) and EUV (He II Ly α, 30.4 nm) corona as well as in the visible spectral range. Several multilayer optics with high reflectivity in the all ranges of interest have being proposed. Since SOLO will fly at the short distance of 0.23 UA at its perihelion, a careful determination of the heat load and the solar wind effect on the multilayers must be carried in order to check if degradation occurs.

To test thermal stability, a thermal analysis experiment has been conceived: the proposed multilayer structures, which are based on different pairs of materials and different capping layers design, must be subjected both to heating and cooling cycles and then to several hours of heating at the provided perihelion temperature. Reflectivity at the different spectral ranges of interest has to be measured before and after each treatment to verify possible degradation. Other useful investigation techniques are TEM, XRR, XPS and AFM.

Determination of the solar wind effect on the same multilayer structures can be obtained exposing same multilayer structure to a proton bombardment at 1 KeV energy. The proton flux on the multilayer was evaluated by considering the average distance of the SOLO satellite from the sun and considering that the proton density depends on the inverse square of the distance from the Sun. Equivalent fluxes have been calculated to reproduce the total dose of proton implanting into the ML in a simulated laboratory experiment lasting few days. Performances degradation is therefore evaluated with same techniques reported above.

8077-16, Session 5

Responses of polymers to laser plasma EUV light beyond ablation threshold and micromachining

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We have investigated responses of polymers to EUV light from laser-produced plasma beyond ablation thresholds and micromachining. We concentrated on bio-compatible polymers such as PDMS, PMMA, and acrylic block copolymers (BCP). PMMA is one of the most extensively studied X-ray-sensitive material. PDMS is commonly used in the fields of bio-technology and micro-fluidics because it sticks to a substrate. Acrylic block copolymer (BCP) can be a more suitable material for layer stack because it sticks to each other and other materials more tightly than PDMS. The EUV processing is a promising basic technique in the field of bio-technology. In particular, it can be applied to bio-sensors such as a planer-type patch clamp device, where precise manipulation of cells is required. The devices could be realized by the precise micro-structures in a scale of a micrometer. In the present work, we generated wide band EUV light in a range of 10-300 eV by irradiation of Ta targets with Nd:YAG laser light at 500 mJ/pulse. For comparison, polymer sheets were irradiated with narrow band EUV light at 11 and 13 nm generated by irradiation of solid Xe and Sn targets, respectively, with pulsed CO_2 laser light. The generated EUV light was condensed onto polymer sheets at a high power density, using an ellipsoidal mirror that condenses EUV light at 100-300 eV efficiently. The EUV light was incident through windows of contact masks on the polymer sheets. We found that through-holes with a diameter of one micrometer can be fabricated in PMMA and PDMS sheets with thicknesses of 4-10 micrometers, at 250 and 230 nm/shot, respectively. The effective ablation of PMMA sheets can be applied to a LIGA-like process for fabricating micro-structures of metals using the practical apparatus. PDMS sheets are ablated if it is irradiated with EUV light beyond a distinct threshold power density, while PDMS surfaces were modified at lower power densities. Furthermore, BCP sheets were ablated to have 1-micrometer structures. Thus, we have developed a practical technique for micromachining of PMMA, PDMS and BCP sheets in a micrometer scale.

8077-17, Session 5

Damage investigations on EUV relevant materials using a table-top LPP source

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In recent years technological developments in the area of extreme ultraviolet lithography (EUVL) have experienced great improvements. Simultaneously, free electron lasers (FEL) are being developed, emitting already radiation in the same wavelength range. Main goal of our research is to utilize the unique interaction between soft x-ray radiation and matter for probing, modifying, and structuring solid surfaces, as well as investigating radiation-induced degradation and damage effects on EUV components like detectors and mirrors.

We present a detailed description of a setup capable of generating and focusing EUV radiation, yielding high EUV energy densities at a high spectral purity. It consists of a table-top LPP source using solid Au as target material. In order to obtain a small focal spot resulting in high EUV fluence, a modified Schwarzschild objective consisting of two spherical mirrors with Mo/Si multilayer coatings is adapted to this source. By demagnified (10x) imaging of the Au plasma an EUV spot of approximately 4 µm diameter (FWHM) is generated with a maximum EUV fluence of ~7 J/cm² (pulse length 8.8 ns).

We give an overview of ablation, damage and degradation experiments on polymers, inorganic materials (silica, calcium fluoride, fused silica) and EUV optics (grazing incidence gold mirrors, Mo/Si mirrors), demonstrating the potential of the system for such kind of studies.

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In more detail we report on ablation studies on PMMA. Additionally, damage probability measurements of grazing incidence Gold mirrors will be presented, including a model for the observed damage mechanism. The experimental results will be summarized in terms of a general statement on damage mechanisms of different materials under intense EUV irradiation.

8077-18, Session 5

EUV-induced ablation and surface modifications of solids

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Extreme ultraviolet (EUV) spans a wavelength range of approximately 5÷50 nm. The EUV radiation can propagate only in vacuum because of strong interaction with any kind of matter. The strong interaction with matter results in EUV absorption in a very thin layer with the thickness of approximately 100nm. If the radiation fluence is sufficiently high, i. e., overcoming the ablation threshold, bond breaking leads to efficient material ablation or at least modification of the near surface layer. The modification can be either physical or chemical. Because of small penetration depth of the radiation the material under the modified layer remains not degraded.

In this work results of investigations concerning ablation and surface modification of polymers and some other solids using a laser-plasma EUV source are presented. The plasma radiation was produced using a gas puff target and was focused with a gold-plated grazing incidence ellipsoidal collector. The collector allowed for effective focusing of radiation of Kr or Xe plasmas within the wavelength range 8 - 70 nm. The materials were irradiated in the focal plane or at some distance downstream the focal plane of the EUV collector. The ablation process was investigated using a scanning electron microscope (SEM) and a quadrupole mass spectrometer (QMS). The surface morphologies of the irradiated polymer samples were investigated using SEM and an atomic mass spectrometer (AFM). The chemical changes were investigated by X-ray photoelectron spectroscopy (XPS). Time resolved investigation of ablation products with QMS revealed significant differences for polymers with different resistance to EUV irradiation. Different kinds of micro- and nanostructures created in near-surface layers of the materials were obtained. Form of the structures depend on a particular material and the EUV exposure. In a case of some polymers even a single shot was sufficient for creation of the visible changes in surface morphology. In a case of inorganic solids visible changes required usually the exposure with tens or hundreds of EUV pulses. XPS investigations revealed chemical changes in near surface layers of materials. Significant differences were revealed in the XPS spectra taken for irradiated and not-irradiated polymers. Significant decrease of functional groups containing oxygen was indicated.

8077-19, Session 5

Particle-induced damage effects on EUV source collector mirror optics

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Exposure of collector mirrors facing the hot, dense pinch plasma in plasma-based EUV light sources to debris (fast ions, neutrals, in-band, off-band radiation, droplets) remains one of the highest critical issues of source component lifetime and commercial feasibility of nanolithography at 13.5-nm. Typical radiators used at 13.5-nm include Xe and Sn. Fast particles emerging from the pinch region of the lamp are known to induce serious damage to nearby collector mirrors. Candidate collector configurations include either multi-layer mirrors (MLM) or single-layer mirrors (SLM) used at grazing incidence.

This talk will present an overview of particle-induced damage and elucidate on the underlying mechanisms that hinder collector mirror performance at 13.5-nm facing high-density pinch plasma. Results include recent work in a state-of-the-art in-situ EUV reflectometry system that measures real time relative EUV reflectivity (15-degree incidence and 13.5-nm) variation during exposure to simulated debris sources such as fast ions, thermal atoms, and UV radiation [1,2]. Intense EUV light and off-band radiation is also known to contribute to mirror damage. For example off-band radiation can couple to the mirror and induce heating affecting the mirror's surface properties. In addition, intense EUV light can partially photoionize background gas used for mitigation in the source device. This can lead to local weakly ionized plasma creating a sheath and accelerating charged gas particles to the mirror surface inducing sputtering. In this overview we will also summarize studies of thermal and energetic particle exposure on collector mirrors as a function of temperature simulating the effects induced by intense off-band and EUV radiation found in EUVL sources. Measurements include variation of EUV reflectivity with mirror damage and in-situ surface chemistry evolution.

1. J.P. Allain, et al., Appl. Phys. A, 100 (1) 2010, 231.

2. J.P. Allain, et al., Appl. Phys. A., 91 (1) 2008, 13-16.

8077-20, Session 6

Structural change induced in carbon materials by electronic excitations

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Carbon is known to have various structures which are separated mutually by a large potential barrier and hence usually stable in ambient environment. For the last decade, however, we have found significant effects of electronic excitations on the structural stability in carbon materials such as amorphous carbon, fullerenes, and carbon nanotubes. The electronic excitations that induce restructuring or damage range from soft X-ray illumination to irradiation with low-energy electrons, the latter including excitations achieved by tunneling electron injection from probe tips of scanning tunneling microscopes (STM). Both of these excitations are characterized by the spatial localization of the primary stimulation: In soft X-ray illumination core electron excitations causes localized absorption of photons at the specific atoms, and in tunnel injection of carriers from STM tips are primarily localized at the injection point. Nevertheless, the mechanism of the excitation-induced atomic displacements can differ depending on the combination of material and excitation method. This talk will overview the current status of research on such anomalous effects in the three different carbon materials each of which has some possible applications.

8077-21, Session 6

Damage formation and characterization with scanning photoemission spectromicroscopy

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A scanning photoemission microscope (SPEM) uses the most direct approach to obtain spatial resolution i.e. the focalization of the incoming x-ray beam. The x-ray SPEM at the Elettra synchrotron light source located at Trieste, Italy de-magnifies the photon beam by means of a Fresnel zone plate. This focusing setup produces very intense beams where the typical photon flux is 1018-1019 photons/(mm2 s). Recently, thanks to the improvement in the quality of the focusing optics, nanostructures as wide as 45 nm have been imaged and characterized. The available range of photon energies (400-800 eV) covers the most intense core levels of the majority of the atomic species making the SPEM an ideal tool for the chemical characterization at the meso- and nanoscale regime. The overall energy resolution achievable in working conditions at room temperature is around 200 meV. In-situ samples can be heated, cooled and biased.

Thanks to these premises the SPEM is an ideal tool for the investigation of soft x-rays induced damages on soft and hard matter samples and their characterization. The unique surface and chemical sensitivity of photoemission combined with microscopy make possible a detail investigation at sub-micron lateral scale.

A overview of photon-induced sample damages produced and/or characterized with the SPEM will be provided dealing with oxide thin films and coatings, organic materials, ablated materials, etc.

8077-22, Session 6

Desorption mechanisms in PMMA irradiated by high order harmonics

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The recent development of intense sources in the XUV range (10-100 nm), such as X-ray laser, Free Electron Laser and High order Harmonics (HoH), allows the study of high flux processes and ultra-fast dynamics in various domains.

At the SLIC facility of CEA-Saclay, we have built a gas-harmonic beamline to investigate the interaction of intense XUV pulse with solids. High Harmonics of an IR laser (Ti:S at 800 nm, 35 fs, 13 mJ/pulse, 1 kHz) are generated in a rare gas cell (Xe). The useful XUV range (40-60 nm) is selected with metallic filters. The harmonic beam is focused with a parabolic mirror to a 10 µm focal spot on sample, leading to a fluence per shot of up to 1 mJ/cm2 (within a typical 10 fs pulse duration).

Studies aimed at understanding the damaging mechanisms caused by XUV irradiation on surface of various samples by systematically varying fluence and exposure time.

For PMMA irradiated in the desorption regime (fluence/shot $\leq$ 0.2 mJ/cm2), the surface presents craters whose profile depends on the dose (Grey [Gy] = 1 J/kg). The crater evolution proceeds from the competition between two main degradation processes, that is chain scission and cross linking. Namely, at low dose ($\leq$ 1 GGy) polymer chain scission is followed by the blow up of the volatile, molecular fragments, forming the crater. At high dose (> 10 GGy) the broken chain-ends, in the near-surface layer of the remaining material, recombine by cross-linking, opposing desorption by surface hardening.

In recent experiment at LCLS FEL facility, PMMA was irradiated by high doses of x-rays at a fluence below the single-shot ablation threshold; the cross-linking signature was identified from Raman spectroscopy. A kinetic model could be adapted for interpreting these original and very promising results.

8077-23, Session 6

Multilayer white beam study

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The degradation mechanisms are a critical issue if multilayers are used as monochromators for white beam synchrotron applications. To quantify the radiation impact x-ray reflectivity measurements before, during, and after white beam exposure were performed.

For the in-situ irradiation study a versatile vacuum chamber was developed and tested using a high power undulator source. The device is equipped with a cooling system for the multilayer samples to distinguish thermal effects from pure radiation induced ones. The x-ray reflectivity was measured at fixed angle of incidence in an energy dispersive mode and as a function of time. The energy dispersive detection allows for the simultaneous observation of the multilayer reflectivity spectrum over a wide range. The white beam study includes various long-term exposures with an incoming load up to 250 W.

Ex-situ x-ray reflectivity measurements and beam imaging were carried out with monochromatic radiation at 8 keV before and after the white beam exposure. TEM analysis provides complementary information on the layer structure in the stack.

Depending on the material system, the total radiation dose, and the sample environment, different degrees of modifications in the multilayer structure were observed.

8077-24, Session 6

Three dimensional measurement of the point spread function of a soft X-ray zone plate via single pixel exposure of photoresists at focus

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We use the monochromatic zone plate focused soft X-rays of scanning transmission X-ray microscopes (STXM) to directly write patterns (sub-40 nm) in common photoresists, analogous to lithography with a focused electron or ion beam. The photon energy tune-ability of STXM has been exploited for chemically selective patterning of multi-component (bilayer [1], trilayer [2]) resists. We also use STXM to investigate and characterize the radiation damage chemistry of thin (20 - 150 nm) polymer/photoresist films by extracting the near edge X-ray absorption fine structure (NEXAFS) signal from an irradiated area as a function of dose with sub-30nm spatial resolution [3].

We encountered a radiation damage spreading phenomenon when patterning with monochromatic focused soft X-rays high doses, which was later determined to be due to the point spread function of the zone plate lens itself. By making a series of single pixel exposures in a photoresist at focus over a controlled dose range we can effectively measure the point spread function of a soft X-ray zone plate in three dimensions. We demonstrate how this novel measurement is sensitive to aberrations of zone plates, and discuss how the information could be valuable feedback toward optimizing zone plate lens fabrication.

This research was performed at Advanced Light Source beamline 5.3.2 (Berkeley, California, U.S.A.) and Canadian Light Source beamline 10ID-1 (Saskatoon, Saskatchewan, Canada) with the support of NSERC and BES-DoE.

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8077-25, Session 7

Radiation damage by secondary electrons within FEL irradiated samples

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An overview on physical mechanisms contributing to the radiation damage within samples irradiated with FEL photons is given.

Photons energies in VUV and X-ray regime are considered.

Microscopic processes participating in the sample dynamics are described in detail. Evolution of irradiated samples is followed, using the particle approach. Applicability of this method is then discussed with respect to the size and structure of irradiated samples.

8077-26, Session 7

Molecular dynamics simulations on time-dependent potential energy surfaces for the study of ultrafast phase transitions and coherent phonons

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Laser induced femtosecond structural changes in diamond, graphite, silicon and germanium are studied theoretically. In an attempt to treat both ionic motion and the changes in the electronic structure with sufficient accuracy, we employ molecular dynamics simulations on the basis of a time-dependent potential energy surface derived from a tight-binding Hamiltonian. The tight-binding description represents a compromise between computational efficiency and a sufficiently realistic treatment of the bonding and electronic structure in the materials. The shape and spectral composition of the laser pulse is explicitly taken into account. This approach is applied to the laser excitation of bulk diamond and allows a study of the conditions under which ultrafast graphitization takes place. A study of graphite in a slab geometry permits the investigation of a preablation mechanism:

The deposited energy is not sufficient for ultrafast bond breaking, but the excitation of intense vibrational motion leads to repulsive interaction between the graphite layers. In the investigation of intense laser excitation of ultrathin silicon films, density modulations and thus the formation of large clusters is observed. By implementing a nonorthogonal tight binding scheme for germanium, we can address the softening of phonon modes in laser induced nonequilibrium. We determine the time scales of the structural response by following the attenuation of relevant Bragg peaks. Recent experiments are in good agreement with predictions from our theoretical approach.

8077-27, Session 7

Electron kinetics in semiconductors and metals irradiated with VUV-XUV femtosecond laser pulses

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When ultrashort laser pulses irradiate a solid, photoabsorption by electrons in conduction or valence band (as well as by ionization of deep atomic shells) produces nonequilibrium highly energetic free electrons gas. We study the ionization and excitation of the electronic subsystem in a semiconductor and a metal (solid silicon and aluminum, respectively). The irradiating femtosecond laser pulse has a duration of ~10 fs, and a photon energy of few tens of femtoseconds.

The classical Monte Carlo method is extended to take into account the electronic band structure and Pauli's principle for excited electrons. In the framework of the method, all the processes are simulated event by event.

In the case of semiconductors this applies to the holes as well. Conduction band electrons and valence band holes induce secondary excitation and ionization processes. We discuss the transient electron dynamics with respect to the differences between semiconductors and metals. For the case of semiconductors it is split into two parts by the band gap. For metals, the electronic distribution is split up into two different branches: a low energy distribution as a slightly distorted Fermi-distribution and a long high energy tail. To thermalize, these excited electronic subsystems need longer times than the characteristic pulse duration. Therefore, the analysis of experimental data with femtosecond lasers must be based on non-equilibrium concepts.

We compare the calculated electron distributions with the spectroscopy data obtained in recent experiments with the FLASH laser in DESY, Hamburg. The comparison allowed us to investigate changes in the selection rules in the transition of electron from the conduction band of aluminum to the 2p states in excited aluminum target. We also calculate a lattice heating by electrons irradiated with photons of different energies. The results suggest that the lattice dynamics is affected by the initial nonequilibrium electronic state.

8077-28, Session 8

Frenkel defect process in amorphous silica

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Synthetic amorphous silica (a-SiO2) is widely used in excimer laser photolithography. Since optical properties of a-SiO2 are strongly influenced by point defects, their structures and formation mechanisms have been studied intensively. Decomposition of an Si-O-Si bond into a pair of oxygen vacancy and interstitial oxygen species is an intrinsic defect process in a-SiO2. It is similar to the creation of vacancy-interstitial pairs in crystalline materials and is regarded as "Frenkel defect process" in an amorphous material. Oxygens are also known to be emitted from a-SiO2 surfaces under irradiation with VUV light. However, most of interstitial oxygen species, the anion part of the Frenkel pair in a-SiO2, lack reliable spectroscopic signatures. Thus, this process has been studied much less than another intrinsic defect process in a-SiO2, a simple cleavage of an Si-O bond, yielding a pair of silicon and oxygen dangling bonds. However, interstitial oxygen molecule (O2), a common form of the interstitial oxygen species, exhibits characteristic infrared photoluminescence at 1272nm. We developed a method to determine the concentration of radiation-induced interstitial O2 through laser excitation of its low-lying electronic states. By measuring concentrations of all defects, produced in these two intrinsic processes under dense electronic excitation with 60Co gamam-rays, it was found that the Frenkel process is dominant over the formation of the dangling bond pairs in high-purity synthetic a-SiO2. Influences of fluorine doping, which is considered to be useful in improving both UV-VUV transparency and radiation hardness, will be presented.

8077-29, Session 8

Damage to low-k porous organosilicate glass from vacuum ultraviolet irradiation

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Vacuum ultraviolet (VUV) irradiation generates trapped charges as well as mobile charges in the bandgap of dielectric films both of which have the potential to cause damage. The amount of trapped charge generated under VUV irradiation depends on photoemission and injection processes. Using a synchrotron as a source of VUV radiation, we determine that trapped positive charges are generated when electrons are photoemitted from defect states in the dielectric bandgap. Conversely, photoinjection of electrons from the substrate into the dielectric repopulates the defect states, reducing the number of trapped charges. The difference in the time integrals of the photoemission and photoinjection (steady-state) currents determines the number of trapped charges generated during irradiation. The defect state locations can be determined with VUV spectroscopy.

Surface potential and C-V characteristic measurements confirm trapped positive charges in the dielectric. With increased VUV dose, an increase in the surface potential and, from the CV characteristics, a corresponding shift in flat-band voltage along with hysteresis appears. Hysteresis indicates the presence of mobile charges in the bandgap. Using the synchrotron, we find that the number of trapped charges generated in porous low-k organosilicate glass (SiCOH) due to VUV depends on the dielectric porosity and the nature of the dielectric-substrate interface. Also, UV curing affects the number of trapped charges.

In addition, an electron cyclotron resonance plasma reactor with a capillary array window that can be placed over the dielectric showed that plasma processing VUV photons were responsible for trapped-charge accumulation within the dielectric. The charged ions primarily stick to the surface of the dielectrics.

The defects in the dielectrics were detected using electron-spin resonance spectroscopy. It is shown that defects are modified by photon bombardment in the plasma rather than ion bombardment. The defect concentration changes as a function of VUV or UV radiation dose. We show that lowering the dielectric constant will lead to increase of the defect concentrations.

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8077-30, Session 9

High-throughput beam splitters for high-order harmonics in soft-x-ray region

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In recent years, there have been several experimental demonstrations of soft-x-ray light sources based on high-order harmonics. These are high energy light sources with ultrashort pulse durations, and can be used in several different applications. This includes attosecond metrology, where they have been used for the direct measurement of infrared electric fields, the observation of two-photon above-threshold ionization, two-photon double ionization and two-photon absorption. At the same time, there have been several demonstrations of soft-x-ray multilayer mirrors. On the other hand, there have only been a few studies covering soft-x-ray filters and beam splitters, because it was thought that their role was limited to acting as spectral selectors in synchrotron radiation beam lines. However, they have played crucial roles in high harmonic applications because they can remove residual pump radiation as well as unnecessary harmonics that are harmful to the measurements.

We demonstrated two high-throughput beam splitters for high-order harmonics in soft-x-ray region, an extremely-flat free-standing thin-film filter and a high-damage-threshold reflective beam splitter. The Al thin-film filter, which is coated with a SiC film to increase its oxidation tolerance, was fabricated on Si wafer and feature superior flatness, less roughness and higher mechanical stiffness than conventional filters. The fabricated filter has a transmittance of 29% at 30 nm. This value is approximately 5 times higher than that of an uncoated filter fabricated using conventional method. And the Si plate beam splitter set at Brewster's angle with respect to the pump wavelength has a reflectivity of 56% at 30 nm. The beam splitter is guaranteed to have a damage threshold of at least 0.8 TW/cm2 (average power density, 0.25 W/cm2) and an attenuation rate of 10-4-10-5 for a 30-fs pump pulse.

8077-31, Session 9

Relaxation and interaction of electronic excitations induced by intense ultra short light pulses in scintillators

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Ultra short high intensity XUV light pulses (below 100 fs) supplied by novel accelerator-based free electron lasers (FEL) [1], by high order harmonic generation (HHG) systems based on a Ti-Sapphire laser or by powerful femtosecond UV-lasers allow investigating relaxation processes and interaction of electronic excitations in scintillators under extreme density conditions. Recent years we have carried out such investigations for different scintillators (tungstates, doped rare-earth oxides, crystals with cross-luminescence) in non-linear regime at the exciting photon energies ranging from resonant conditions near intrinsic absorption edge to the deep core levels by means of time-resolved luminescence spectroscopy [2-5]. Such investigation help to clarify causes of non-proportional response of scintillators, which is one of the key factors restricting their efficiency and energy resolution. The spatial density of thermalized electrons and holes, their transport and interaction as well as competition between radiative and non-radiative recombination are the main factors influencing the response of light converting materials. The decrease of the total luminescence yield and the shortening of the luminescence decay time as a function of excitation density are the main experimental evidences revealed. The latter one allows development of the quantitative model describing interaction of closely spaced excitations [6]. Different light sources in wide excitation energy range gave us an opportunity to study such interaction for resonantly formed single excitations as well as for multiple spatially confined excitations created in inelastic scattering process of hot electrons. Defect formation will be also discussed.

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8077-32, Session 9

Saturation of Ce:YAG scintillator exposed to ultrashort VUV, XUV and hard X-ray radiation pulses

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We report on investigation of saturation phenomena of the Ce:YAG scintillator crystal under influence of intense, femtosecond VUV, XUV and hard X-ray radiation pulses. The study was performed at the DESY and SLAC FEL sources delivering photons at 90 nm, 13.5 nm and 0.15 nm wavelength. The saturation of the photon yield occurs at the energy deposition level of 25±15 J/cm3 into the crystal in the photon energy range 10 eV - 8300 eV. This is consistent with earlier findings [1] that the internal radiance efficiency ksi does not depend strongly on the energy of incident photons ksi=0.035 +/- 0.015 in the range 10eV - 100000 eV. The results obtained in this report can be applied in prediction of saturation effects for imaging diagnostics of bright photon and particle beams provided by novel accelerators. The discussion of possible saturation mechanisms follows.

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8077-33, Session 9

Damage to dry plasmid DNA induced by nanosecond XUV-laser pulses

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Ionizing radiation induces a variety of DNA damage including single-strand breaks (SSBs), double-strand breaks (DSBs), abasic sites and oxidized lesions. Most theoretical and experimental studies have been focused on DNA strand scissions, in particular production of DNA double-strand breaks. DSBs have been proven to be a key damage at a molecular level responsible for the formation of chromosomal aberrations, leading often to cell death [1, 2]. The complexity of lesions produced in DNA by ionizing radiations is thought to depend on the amount of energy deposited at the site of each lesion [3]. We have studied the nature of DNA damage induced directly by the pulsed 46.9-nm radiation provided by a capillary-discharge Ne-like Ar laser (CDL) [4]. Surface doses 3.5-40 kGy were delivered with a repetition rate of a few Hz and an average pulse energy ~ 1 μJ at the sample surface. A simple model DNA molecule, i.e., dried closed-circular plasmid DNA (pCDNA3), was irradiated. The agarose-gel-electrophoresis was engaged in sample analysis making it possible to determine both SSB and DSB yields. Results are compared with a previous study of plasmid DNA irradiated with a single sub-nanosecond 1-keV X-ray pulse produced by a large-scale, double-stream gas puff target, illuminated by sub-kJ, near-infrared (NIR) focused laser pulses at the PALS facility (Prague Asterix Laser System) [5].

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8077-34, Session 9

Study on the lifetime of Mo/Si multilayer optics with pulsed EUV-source at the ETS

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As EUV lithography is on its way into production stage, studies of optics lifetime under realistic conditions become more and more important. Due to this fact an Exposure Test Stand (ETS) has been constructed at XTREME technologies GmbH in collaboration with Fraunhofer IOF and with financial support of Intel Corporation. This test stand is equipped with a pulsed Xe DPP source and allows for the simultaneous exposure of several samples in different gas atmospheres. This contribution will introduce the experimental set-up at ETS and give an update on recent modifications. Selected results from contamination and cleaning experiments conducted at ETS will be shown and future perspectives of ETS will be discussed.

Comparative lifetime studies of Mo/Si multilayer mirrors with different capping layers (Ru, TiO2, Nb2O5) have been conducted at the ETS. For this work an exposure set-up was used, which allows the homogeneous exposure of up to four samples with an exposed area larger than 35 mm2 on each sample at an intensity of 25 mW/cm2. After a recent modification of the ETS the change of the optical configuration of the ETS is possible. In this alternative set-up exposures with intensities up to 100 mW/cm2 are possible. Although in this configuration the exposed area becomes smaller (~10 mm2), the simultaneous exposure of two samples is possible and the exposed area on each sample is sufficiently large for the application of characterization techniques like EUV reflectivity measurements and X-ray photoelectron spectroscopy (XPS). This set-up was applied for a comparative study of carbon contamination rates induced by EUV radiation from the pulsed DPP-source at XTREME with contamination rates induced by synchrotron radiation. Further, in this set-up the EUV-induced cleaning with different cleaning gases was investigated. The enhancement of EUV-induced cleaning by addition of a second gas to the cleaning gas could be demonstrated.

8077-35, Poster Session

Damage of amorphous carbon induced by x-ray femtosecond free electron lasers pulses

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Free-electron lasers (FEL) deliver femtosecond millijoule light pulses in the soft to hard x-ray photon energy range. The interaction of such light pulses with x-ray mirror coating is a very important issue for the efficient operation of these facilities. Hence, understanding the interaction mechanisms occurring at the surface of the optical elements is a critical factor.

We investigate the damage caused by an FEL pulse on x-ray mirror coatings. The interesting candidate for this purpose is amorphous Carbon (a-C). We will present results of damage studies performed at two different Free-Electron Laser facilities: FLASH in Hamburg and LCLS in Stanford. The experiments at FLASH were performed with two different photon energies (91 eV and 177 eV) and under different geometrical conditions: normal and grazing incidence, above and below the critical angle. Amorphous-Carbon samples with 40 and 900 nm thickness coated on silicon (Si) substrate were used. The damage fluence threshold corresponding to each experimental condition was determined, in particular the damage fluence threshold of a 40 nm a-C sample under 4.3 ° grazing incidence angle at 177 eV photon energy was found out to be 43.7mJ/cm2. The experiments at LCLS were performed at 830 eV photon energy and normal incidence angle. For the 1400 nm thick a-C sample, a fluence threshold of 0.27 J/cm² was determined. To grasp a better understanding of the structural changes, the damage spots were investigated by Atomic Force Microscopy and Micro Raman Spectroscopy. The corresponding results indicate that the irradiated a-C undergo a phase transition leading to formation of nanocrystallites of graphite.

8077-36, Poster Session

Laser-produced plasma EUV source at 6.7 nm as a future EUV source

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The development of an efficient and high power extreme ultraviolet (EUV) laser-produced plasma (LPP) source is important in many applications, such as lithography, material science, and biological imaging near the water window. Here, we investigate LPP emission coupled to a Mo/B4C multilayer mirror with peak reflectance of 40% at 6.5-6.7 nm.

A Q-switched Nd:YAG laser at 1064, 532 and 355 nm producing maximum pulse energies of 2, 1 and 0.4 J and pulse duration of 10, 8 and 7 ns (FWHM), respectively was perpendicularly focused on planar Gd, Tb, and Gd2O3 targets. The focused intensity ranged from 1010 to 1013 W/cm2 with focal spot sizes from 30 to 300 microns and time-integrated spectra obtained by a thermoelectrically cooled back-illuminated x-ray CCD camera. The absolute EUV energy, which was positioned at 45 with respect to the incident laser axis, was measured with a calibrated EUV energy meter equipped with a Mo/B4C multilayer mirror and a Zr filter. All EUV CEs presented are calculated from the emission energy at 6.7 nm within a 2 % bandwidth (BW) for a solid angle of 2π sr, over which the radiation was assumed to be isotropic.

We observed spectra of Gd LPPs at different focal spot diameters, laser intensity, laser wavelength, and initial target density. The typical time-integrated emission spectra produced strong broadband emission around 6.7 nm. According to previous work, the highest emission intensity was found at a focal spot diameter larger than 300 microns, to reduce plasma hydrodynamic expansion loss effects. The in-band emission at 6.7 nm ± 1%, at a spot diameter of 35 microns, was observed to be lower than that at 210 microns.

We observed the effect of differing critical electron densities at a laser intensity of approximately 1.6 × 1012 W/cm2. The in-band emission is attributed to hundreds of thousands of near-degenerate resonance lines which overlap to form an unresolved transition array (UTA).
To reduce the effect of self-absorption, it is important to study the influence of the initial concentration of Gd in the target. In the case of the lower-density Gd2O3 target, we observed enhanced spectral purity and EUV CE. This data suggests that it is important to use shorter pulse duration irradiation and low electron density plasmas to increase the EUV CE and the spectral purity.

In summary, the in-band emission strongly depends on the plasma volume, electron temperature and plasma hydrodynamic expansion loss effects. The maximum CE was observed to be 1.3% with Gd2O3 and the spectral purity was also improved.

We will show and discuss the wavelength dependence on the spectral behavior and conversion efficiency in future work.

8077-37, Poster Session

Thermal stability on Mo/B4C multilayers

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Recent developments at FLASH (Free electron LASer at Hamburg, Germany) have enabled experiments at wavelengths shorter than 6.5 nm. Normal incidence optics for wavelengths shorter than 12.5 nm (Si K edge) are also of interest for next generation extreme ultraviolet lithography (EUVL). We investigated the effect of annealing temperature and annealing time on reflectance, stress and wavelength stability of Mo/B4C multilayers for 6.5 nm wavelength. We will present our results on thermal stability, which we extracted from stress, small and large angle X-Ray Diffraction, and normal incidence synchrotron reflectivity measurements, for the temperature range between 100°C and 900°C and discuss stress reduction methods.

8077-38, Poster Session

FEL multilayer optics damaged by multiple shot laser beam: experimental results and discussion

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The irradiation effects of multiple femtosecond shots of a 400 nm laser beam with estimated fluences of some tens of mJ/cm2 on a EUV Mo/Si multilayer have been studied. The study has been motivated by the need of multilayer Mo/Si optics for the delay lines of the FEL source FERMI@Elettra, where these mirrors will be used to reflect 100 fs pulses at 13 nm with a fluence of some mJ/cm2. The analysis was carried on by means of different techniques as EUV and soft X-ray reflectivity, XPS, Total Electron Yield and Standing wave enhanced XPS [1]. Measurements have been performed at the BEAR synchrotron beamline @ Elettra. Simulations have been carried on by means of a new home made software 'OPAL' for the calculation of the intensity of the electric field inside the stratified medium [2]. Preliminary measurements have been performed also with a new fluorescence detector. A simple thermodynamic model have been also used to investigate the propagation of heat during the laser irradiation. AFM and SEM surface images have been also acquired. We observed a significant change in the multilayer performance at fluences of 100 mJ/cm2 and above with a significant reduction of reflectivity. Spectroscopic analysis allowed to correlate the decrease of reflectivity with the degradation of the multilayer stacking, ascribed to Mo-Si intermixing at the Mo/Si interfaces of the first layers, close to the surface of the mirror.

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8077-39, Poster Session

Handling the carbon contamination issue at SOLEIL

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Before the first photon beam was delivered to the beamlines, SOLEIL scientists tried to anticipate the carbon contamination on optics, with for instance the outgasing of chambers by exposure to the beam without optics. In spite of these efforts, problems appeared on UV-VUV and soft X-ray beamlines : photons flux losses over the whole the spectrum, holes at specific wavelengths (9-13 eV, Carbon K edges) depending on the thickness of the C-coating and modifications of the horizontal-to-vertical polarization transmission ratio. The visual characteristics of this contamination consist in a gray/black line over the beam footprint. Since then, two cleaning processes have been implemented successfully on two SOLEIL beamlines (in UV-VUV and soft X-ray), namely in-situ O plasma and in situ ozone generation via UV lamps. A dedicated transverse group is currently working on the improvement of the cleaning processes, the metrology of the optics before and after cleaning and the study of the carbon coating building up in link with possible strategies to prevent, or slow down the contamination process. The presentation will describe this joint effort at the SOLEIL lab level.

8077-40, Poster Session

Blistering behaviour in Mo/Si mirrors for EUV lithography

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Development of EUV optics with lifetimes high enough for photolithographic applications requires understanding of ion-induced processes on the multilayer surfaces. Bombardment of the multilayer structure by EUV-driven plasma's and ion-based techniques are among the examples of relevant ion-surface interactions. We have observed that severe damage to the surface of Mo/Si multilayer mirrors can be produced by reactive gas ion bombardment. The damage is represented by subsurface void formation identified by SEM, AFM and TEM measurements. The voids are formed at specific depth locations in the multilayer structure. The extent of damage in terms of height and diameter of voids is strongly dependent on exposure conditions. There is a fluence threshold after which the voids start to appear and an enhancement of their size for longer exposure times or higher ion fluxes. Irradiations at elevated temperatures lead to extensive increase of the features observed. This fact allows us to infer that a diffusion-driven gas accumulation in the mirror plays a role in void formation. The presence of trapped gas in the system after ion exposure is confirmed by ERD measurements. A tentative model of void growth is based on creation of ion-induced stress in the system which is released via delamination of the surface region of the mirror. In the extreme, this could lead to flaking of some surface area of the mirror and potentially cause enhanced oxidative damage of the structure underneath or acceleration of carbon contamination growth.

8077-41, Poster Session

Micromachining of polydimethylsiloxane induced by laser plasma EUV light

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Polydimethylsiloxane (PDMS) is fundamental materials in the field of biotechnology. Because of its biocompatibility, microfabricated PDMS sheets are applied to micro-reactors and microchips for cell culture. Conventionally, the micro-structures were fabricated by means of cast or imprint using molds. These methods have high productivity of micro-structures, however it is difficult to fabricate the structures at high aspect ratios such as through-holes/vertical channels. The fabrication of the high-aspect structures would enable us to stack sheets to realize 3D fluidic circuits. In order to achieve the microfabrication, direct photo-ablation by short wavelength light is promising. So far, there has been no report on photo-direct machining of PDMS, to our knowledge. In the previous works, we investigated ablation of inorganic transparent materials such as silica glass induced by irradiation with laser plasma EUV light. We achieved smooth and fine nanomachining. In this work, we applied our technique to PDMS micromachining. We irradiated a Ta target with Nd:YAG laser light to generate light in a range of 10-300 eV. In order to condense EUV light onto PDMS surfaces at high power density, we used an ellipsoidal mirror. In front of PDMS sheets, we placed a Zr filter that transmit EUV light of 50-200 eV. We found that PDMS sheet is ablated at a rate up to 230 nm/shot. It should be emphasized that through hole with a diameter of 1 micrometer is fabricated in PDMS sheet with a thickness of 4 micrometers. Thus we demonstrated that the micro structures at high aspect ratios of PDMS sheets are fabricated by laser plasma EUV light.

8077-42, Poster Session

Computer simulation of short-wavelength laser ablation: the XUV-ABLATOR code

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This work presents a model for XUV radiation-induced ablation based on the computer code ABLATOR by A. T. Anderson in the mid of nineties (LLNL, [1]). ABLATOR is a one-dimensional Lagrangian finite difference code, which means that zone boundaries move with the material and mass in each zone remains constant (no mass flow as in an Eulerian formulation). Every zone interacts only with zones adjacent to it. For a particular zone, state quantities such as internal energy, temperature, pressure, density, etc. are defined, while for a node of two zones acceleration, velocity and position are calculated. ABLATOR was originally developed for numerical simulation of ablation of the materials proposed for first walls of inertial confinement fusion (ICF) reactors, induced by broad-band emission (~ keV) from NOVA-driven hohlraum targets. Modification of ABLATOR was made to perform simulations by radiation with relatively short radiation attenuation length and to include polymer chain scissions for the ablation of an organic polymer. The modified code is named XUV-ABLATOR. The XUV-ABLATOR code was used to predict ablation characteristics of silicon, silica and Poly(methyl methacrylate) - PMMA irradiated by several types of short-wavelength laser radiation with different wavelengths and pulse durations.

[1] Anderson A. T.: X-Ray Ablation Measurements and Modeling for ICF Applications. Lawrence Livermore National Laboratory, 1996, UCRL-LR-125352

8077-43, Poster Session

Electron kinetics in liquid water excited with a femtosecond VUV laser pulse

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We describe theoretically the interaction of an ultrashort VUV-XUV laser pulse with liquid water. Incident photons ionize water molecules and create free electrons. These excited electrons interact via elastic collisions with other water molecules and produce secondary electrons due to ionization. For the laser pulse we assume an average photon energy of a few tens to a few hundreds eV and a gaussian shape with a width of 10fs.

To track each free electron and its collisions event by event, we use an extended Monte Carlo method [1]. First, we calculate the realized penetration depth of the photons. Next, we compute the cross sections for the free electrons referring to ionization and elastic collisions. Further, we evaluate mean free paths of these electrons, and finally we get the energy loss due to elastic collisions or the energy transfer to secondary electrons due to ionization. All the secondary electrons are included in the calculations in the same manner. This approach allows us to describe a transient non-equilibrium behaviour of irradiated water at femtosecond timescales.

As results we present the electron kinetics during laser excitation. We calculate the transient electron- and energy- distributions as a function of depth. Furthermore, we exhibit a time resolved description of the total amount of electrons to show their rapid increase in numbers. We also show the corresponding energy redistribution: change in the kinetic energy of excited electrons, increase of the energy of holes, and energizing of water molecules via elastic collisions.

[1] N. Medvedev and B. Rethfeld, New Journal of Physics 12 (2010) 073037.

8077-44, Poster Session

Radiation damage to molecular solids exposed to multiple shots of x-ray laser below the single-shot ablation threshold

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Solid materials irradiated by energetic photons can be eroded in two modes, depending on radiation intensity. High average, low-peak power sources, e.g., synchrotron radiation and high-order harmonics, induce desorption of the material at a low etch rate. Contrary to that, the high-peak-power radiation delivered to the surface in focused beams of XUV/x-ray lasers usually causes a massive removal of the material even by a single-shot. In this contribution, an effective material erosion is reported in poly(methyl methacrylate) - PMMA exposed to multiple accumulated pulses generated by free-electron x-ray laser LCLS (Linac Coherent Light Source, tuned at photon energy 830 eV in this study, operated at SLAC, Menlo Park, CA) at a fluence below the single-pulse ablation threshold. The effect is caused by polymer chain scissions initiated by single photons carrying enough energy for breaking several C-C bounds. High efficiency of the erosion should be caused by a correlation of the single-photon effects. The existence of such correlations is supported by the finding that erosion efficiency is dose rate dependent. The sub-threshold damage exhibits also a non-linear dose dependence which is cause by competition of chain scission with polymer cross-linking. The cross-linking was proven by Raman spectroscopy of irradiated polymer.

8077-45, Poster Session

Short-wavelength ablation of lead compounds

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The recent commissioning of a X-ray free-electron laser triggered an extensive research in the area of X-ray ablation of high-Z, high-density materials. Such compounds should be used to shorten an effective attenuation length for obtaining clean ablation imprints required for the focused beam analysis [1-3]. Compounds of lead (Z=82) represent the materials of first choice. In this contribution, single-shot ablation thresholds are reported for PbWO4 and PbI2 exposed to ultra-short pulses of extreme ultraviolet radiation and X-rays at FLASH and LCLS facilities, respectively. Interestingly, the threshold reaches only 150 mJ/cm2 at 0.62 nm in lead tungstate although a value of 1.2 J/cm2 is estimated according to the wavelength dependence of an attenuation length and the threshold value determined in the EUV spectral region, i.e., 79 mJ/cm2 at a FEL wavelength of 13.5 nm. Mechanisms of ablation processes are investigated to explain this discrepancy.

Note: The corresponding author presents these results for the LCLS Beam Characterization Collaboration and FLASH Peak Brightness Collaboration.

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8077-46, Poster Session

Ablation of ionic crystals induced by capillary-discharge XUV laser

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Various solid halides (e.g., LiF, CaF2, etc.) were irradiated by nanosecond pulses of 46.9-nm radiation provided by 10-Hz capillary-discharge Ne-like Ar laser (CDL). Single-shot damage thresholds were determined in these materials using the CDL beam focused by a Sc/Si multilayer-coated spherical mirror. Irradiated samples have been investigated by Nomarski (DIC - Differential Interference Contrast) microscopy, Raman spectroscopy with the spatial resolution, atomic force microscopy (AFM), optical profiler (WLI - white light intereferometry) and so on. After an exposure by a certain number of CDL pulses, an ablation rate can be calculated from AFM measured depth of the crater created by the XUV ablation. Potential use of XUV ablation of ionic crystals in pulsed laser deposition (PLD) of thin layers of such a particular material, which is hard to ablate by a conventional UV-Vis-NIR laser, is tested and discussed in this contribution.

Conference 8078: Advances in X-ray Free-Electron Lasers: Radiation Schemes, X-ray Optics and Instrumentation

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8078-01, Session 1

FERMI@Elettra, a seeded free electron laser source for a broad scientific user program

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After less than two years of commissioning the FERMI@Elettra free electron laser is now entering into the operation phase and is providing light to the first user experiments. To reach the final ambitious goals of providing high power coherent pulses with fundamental wavelengths as short as 4 nm the system will need further studies and some additional commissioning periods in 2011 to fine tune the major systems such as the electron gun and the main accelerator. Nevertheless, FERMI is already able to provide users with a light that has characteristics that allow one to perform experiments not possible with other user facilities.

Based on a 1.5-GeV electron linear accelerator, FERMI@Elettra has two seeded FEL lines that cover the whole spectral range from 100 nm down to 4 nm with fully coherent pulses. The use of the high gain harmonic generation scheme initiated by a tunable laser in the UV allows FERMI to produce light characterized not only by transverse coherence but also by a very high temporal coherence. The use of specially designed undulators allows full control of the FEL polarization and can be continuously varied from linear to circular in any orientation or ellipticity. Here we will report about the first results and the future plans for FERMI@Elettra.

8078-02, Session 1

Development of X-ray Optics and beamlines for XFEL at SPring-8

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A joint project team of RIKEN and JASRI has constructed an XFEL facility in the SPring-8 site. We are planning to start the beam commissioning from the end of February, 2011. The first XFEL beamline covers a photon energy range from 4 to 30 keV with the beamline optical system. A fs-synchronized laser system, a K-B focusing system will be installed in the initial phase. I will summarize these latest status, and present a perspective on development of XFEL applications and instrumentation.

8078-03, Session 1

Scientific progress at SPARC

M. Ferrario, Istituto Nazionale di Fisica Nucleare (Italy)

The primary goal of the SPARC project is the commissioning of the SASE FEL operating at 500 nm driven by a 150-200 MeV high brightness photoinjector. Additional experiments have been performed also in the HHG Seeded configuration at 266, 160 and 114 nm. The recent successful operation of the SPARC injector in the Velocity Bunching (VB) mode (bunches with 1 kA current with emittance of 3 mm-mrad have been produced) has opened new perspectives to conduct advanced beam dynamics experiments with ultra-short electron pulses able to extend the THz spectrum and to drive the FEL in the SASE Single Spike mode. Moreover a new technique called Laser Comb, able to generate a train of short pulses with high repetition rate, has been tested in the VB configuration. Two electron beam pulses 300 fs long separated by 1 ps have been characterized and the spectrum produced by the SASE interaction has been observed. In this talk we report the experimental results obtained so far.

8078-04, Session 1

The SwissFEL facility and its preliminary optics beamline layout

P. Oberta, U. Flechsig, R. Abela, Paul Scherrer Institut (Switzerland)

The planned XFEL at the Paul Scherrer Institut, the SwissFEL, is a fourth generation light source. Meanwhile the first hard X-ray FEL was taken into operation, the LCLS at Stanford, USA. Two further hard XFEL are in construction. One in Hamburg, Germany and the second at SPring-8, Japan. Thanks to the beam properties of the XFEL, these new sources promises to bring novel insights and breakthroughs in many scientific disciplines.

For engineers and designers new challenges arise in terms of material choice, damage thresholds and beam property conservation. The Swiss Light Source optics group is currently working on the beamline optics design of the SwissFEL beamlines. The preliminary optics design of the two undulator beamlines which serves six experiments will be presented. Several beamline designs have been evaluated. Beam deflection and splitting via mirrors and diamonds is presented. The SwissFEL is planned to be operational in 2016.

8078-05, Session 1

ZFEL: a compact, soft X ray free-electron laser in the Netherlands

R. Hoekstra, Univ. of Groningen (Netherlands)

In this contribution the plans to construct a compact soft X-ray FEL facility at KVI, University of Groningen, the Netherlands will be outlined. The facility is named ZFEL in honor of the Groningen Nobel laureate Frits Zernike. This new facility will be based on a normal-conducting electron linac that will be driven by a RF photo-injector and X-band acceleration structures with an acceleration gradient of 100 MeV/m. In the first stage of the project we will produce X-ray laser light in the water window at a wavelength of approximately 4 nm. In the second stage of the project the wavelength will be brought down to 0.8 nm. Seeding techniques will be essential ingredients to ZFEL operation. The entire length of the FEL will be on the order of 100 meters. The facility is meant as an international user facility with a strong basis of local AMO, material science and biochemistry groups at the KVI and the Zernike Institute for Advanced Matarials. The design and construction will be a collaborative effort with contributions from research groups from almost all Dutch universities and research institutes.

8078-06, Session 2

Ultrafast atomic and molecular photoionization at the LCLS

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The atomic, molecular and optical physics instrument at the LCLS has been used for approximately 30 experiments at the LCLS x-ray free electron laser at the SLAC National Accelerator Laboratory. The instrument has been used to study the interaction of ultrafast and ultraintense x-rays with atoms, molecules and clusters as intended but has also been used in the study of warm dense matter, material damage, and inorganic and biological particle imaging. Initial experiments on the ionization of atoms and molecules conducted in the fall of 2009 have already resulted in the publication of five peer-reviewed articles at the time of writing of this abstract, with many more to follow. In one of the first experiments at the LCLS, neon atoms were subjected to the full power of the LCLS pulse focused to a waist of ~1um. Depending on the photon energy, pulse energy and duration of the pulse, charge states of up to Ne10+ were observed. The experimental results could be explained using a rate-equation based model of the ionization process. In addition to understanding the dynamics of the ionization processes, the results indicated that the pulse duration reported by the accelerator overestimated the true duration of the x-ray pulse. Photoionization of aligned molecules was demonstrated in a later experiment where N2 molecules were adiabatically aligned using a pulsed Ti::sapphire laser. In addition to determining the alignment dependence of the photoionization cross section, a technique for determining the relative arrival time of the x-ray and IR laser pulses was developed and subsequently used as a diagnostic tool of the laser - x-ray timing. Results from these and other recent AMO experiments at LCLS will be presented.

8078-07, Session 2

Coincidence experiments at FELs

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XUV free-electron-lasers enable investigations of highly non-linear phenomena, i.e. the simultaneous interaction of few photons with atoms or molecules at XUV photon energies, a regime that was not accessible before. In addition, exploiting the short pulse lengths, ultra-fast pump-probe experiments with fs time resolution can be performed in order to trace the dynamical evolution of excited molecules. Here we report on benchmark experiments of fundamental few-photon - few-electron processes in comparison with theoretical models. In addition results of recent pump-probe measurements will be discussed, where a split-mirror was used to slice the FEL pulse into two parts that are time delayed with respect to each other. Both beams are focussed and merged inside the gas-jet target of our reaction microscope. Experimental results will be presented and discussed in terms of possible multiple ionization pathways due to the instantaneous or sequential absorption of several photons.

8078-08, Session 3

Single particle imaging with soft X-rays at LCLS

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X-ray free electron lasers (XFELs) have the capability to determine the structures of non-periodic objects, including cells, viruses and aerosols. The intensity and short pulses of linear coherent light source (LCLS) allow structural information to be recorded in the diffracted x-rays before the particle is destroyed. Using iterative reconstruction methods [1], diffraction patterns can be phased and the structure of the sample recovered.

This technique opens up exciting opportunities for biological imaging, since the structure of cells can be imaged without the need for freezing, staining or crytstallization. If the object is repeatable multiple diffraction patterns can be assembled into a three-dimensional volume, which can be then be phased to obtain the three-dimensional structure.

XFELs also provide an opportunity to study aerosols and airborne particulate matter in situ. Unlike existing electron-microscopy techniques which require these particles to rest on a substrate, with an XFEL these particles can be imaged at high resolution in their native gas phase and in greater volume.

Here we present results of coherent diffractive imaging experiments performed at the LCLS with soft X-rays (1-2keV). Samples were injected into the XFEL beam as an aerosol focused with an aerodynamic lens [2]. Biological samples that were imaged include the Mimivirus and the T4 bacteriophage. Examples of particulate matter that were imaged include iron nanorices and aggregates of latex

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spheres.

These experiments have motivated further development of reconstruction techniques and novel methods for phasing diffraction patterns. The method of reconstructing dark-field images has been developed for cases where the missing data in the beamstop significantly complicates phasing of the entire pattern. The exploration of novel approaches for reconstructing aggregates of spheres will also be discussed.

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8078-09, Session 3

Ultrafast pump/probe diffraction and spectroscopy experiments with FEL radiation: setup development from the soft to the hard X-rays with the aim of studying chemical processes

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Recent developments of highly intense ultrashort X-ray radiation generated with the soft X-ray free electron lasers (FLASH) and the hard X-ray FEL (LCLS) allows for new kind of diffraction and spectroscopy experiments in chemistry and biochemistry [1-3]. The additional coupling of an optical femtosecond laser enables for ultrafast time-resolved experiments of that kind: the optical laser excitation can be used to change the state of matter, to generate structures far away from equilibrium and initiate chemical or biochemical reactions with the advantage of an initial, optically well-defined and coherent excitation of the sample. The FEL pulse is then used to probe structure and electron evolution of the transiently formed state. By varying the time delay between optical laser pump and X-ray probe it is possible to perform these experiments in a time-resolved manner on an ultrafast timescale.

For that purpose we developed a multipurpose vacuum chamber which function is to be used in the pump/probe diffraction / scattering and spectroscopy experiments with FEL radiation. By using a liquid jet setup to deliver the sample into the chamber it is possible to overcome the difficulties coming from the fact that a single shot of the FEL radiation is sufficient to induce irreversible damage to the sample. The refreshment of the sample allows for the experiments with the repetition rate of up to the MHz regime. The liquid jet nozzle size will be in the sub-micrometer range. This multipurpose chamber is in particular suited for chemistry and biochemistry experiments in solution.

We will present our current multipurpose chamber [4] and show plans how to extend it for the hard X-rays experiments. The outline of the detailed setup and configuration and characteristic performance parameters of the spectrometer and diffraction detectors will be discussed during the presentation.

[1] I. Rajkovic et al, Phys Rev Lett 104, 125503 (2010).

[2] J. Hallmann et al, J. Phys. B: At. Mol. Opt. Phys. 43 194009 (2010).

[3] P. Wernet at all, LCLS experiments Sep 2010, in preparation.

[4] I. Rajkovic et al, Rev Sci Instrum 81, 045105 (2010).

8078-10, Session 4

Current status of precision mirror development for coherent X-rays

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We developed precision fabrication and measurement methods, such as elastic emission machining, microstitching interferometry, and relative angle determinable stitching intrferometry, to realize nano-focusing mirror devices for coherent X-rays. In the last year, we achieved 7 nm focusing of 20 keV X-ray by using Pt/C multilayer mirrors with an on-site wavefront phase measurement and correction method. The on-site phase-error measurement is based on a phase retrieval method using precisely measured intensity-profiles near the beam waist. A bendable mirror is placed upstream of the focusing mirror to compensate the wavefront error due to the imperfection of focusing devices.

We are also developing imaging mirror devices using Advanced KB optics, in which four total-reflection mirrors are used to realize Wolter-type optics, for the one-shot imaging in XFEL experiments. In a one-dimensional resolution test of the optical system, we achieved a diffraction-limited performances such as sub-50 nm resolution.

The details of the latest statuses about these two topics will be presented.

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8078-11, Session 4

KB Mirrors for the LCLS hard x-ray free electron laser

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The Linac Coherent Light Source at SLAC National Accelerator Laboratory recently became the first operational hard x-ray Free Electron Laser in the World. The very intense highly coherent beam produced by such a machine gives rise to very stringent demands on optical systems. In particular, the performance of x-ray mirrors needed for use with FELs requires the development of optics that are significantly better than what has typically been used to date with existing x-ray sources.

The Coherent X-ray Imaging instrument at LCLS aims to image small objects beyond the classical damage limit. In the long term, the goal is to achieve sub-nanometer imaging of single biological molecules. In order to make this goal possible, high quality focusing elements are required. These focusing optics must minimally distort the wavefront of the beam, be capable of withstanding a high peak power, be achromatic and capable of producing a diffraction-limited spot.

The first set of focusing mirrors for the CXI instrument have been specified, procured and will be installed in early 2011. Simulations were performed to define the requirements of the system. Then further simulations were performed using the metrology results on the fabricated optics to simulate the expected beam profile at and near the focus. Early commissioning of the mirror system is planned for February 2011. We intend to present some of these commissioning results and present a preliminary comparison between the real and simulated performance of the system.

8078-12, Session 4

Diffractive optics for hard X-FEL radiation

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(United States)

We report on recent developments of Fresnel zone plates for the nanofocusing of hard XFEL radiation and for metrology on XFEL beam line components.

The focusing of hard X-FEL radiation to tiny spot is a prerequisite for many experiments proposed for LCLS and other x-ray laser sources. In particular, coherent x-ray diffraction imaging (CXDI) of single particles or even molecules requires the focusing down to the 100 nm level. X-ray mirrors and refractive lenses are considered for this end, however, such devices are limited in resolution by aberrations rather than by diffraction, especially when they have apertures big enough to accept the full beam cross sections. This leads to an unknown wave front in the interaction volume of CXDI experiments, impeding a consistent data analysis. Fresnel zone plates (FZPs) are capable of providing a clean, undistorted wavefront. The main issue is the radiation hardness of these devices. We have developed a novel type of FZPs based on diamond. First experiments at the XPP end station of the LCLS laser at 8 keV showed that these devices were not affected by the full beam, whereas conventional gold zone plates are destroyed within seconds. The devices were able to accept the full LCLS beam, and to focus it to spot sizes on the order of 100 nm with acceptable efficiency.

Moreover, we have implemented a hard x-ray grating interferometer to measure the wavefront properties at the XPP experimental station. Using a moiré technique, the device it is capable of recording the complete wave front, with an angular sensitivities on the order of 10 nrad. We have applied several interferometer geometries at 8 keV photon energy as a diagnostics tool for the characterization of the optical components, including the high energy offset mirrors, harmonic rejection mirrors, and the double crystal monochromator. In addition we present first results on the analysis of the divergent beam behind a refractive focusing lens in order to derive the focal spot size and the wave front in the beam waist.

8078-13, Session 4

Multilayer XUV/SXR beam splitters for short-wavelength FEL applications

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Multilayer coated optics is used to control XUV and soft X-ray (SXR) radiation in many fields of science and technology, like advanced photolithography, XRF analysis and space research. A developing field is the application in experiments at short-wavelength Free Electron Lasers (FELs), the new generation very intense XUV and SXR radiation sources. A particularly appealing but challenging application, are multilayer based XUV beam splitters, required for e.g. pump-probe experiments, interferometry, parallel user operation at FELs, measurements of the time structure of FEL pulses or for online wavefront diagnostics. However, the high absorption of the short wavelength radiation necessitates the use of extremely thin, and thus delicate membranes as mirror substrates. We are developing and characterizing XUV amplitude division beam splitters, based on a semitransparent membrane coated with a multilayer Bragg reflector. The main scientific topics addressed are: (a) the development of stress-free multilayer coatings on thin (50 nm thick) membranes, (b) optimization of the membrane and coatings with respect to the reflectivity, absorption and transmission, wavefront perturbation and scattered radiation. At the FOM Institute for Plasma Physics Mo/Si multilayers were deposited on 50 nm thin SiN membranes with lateral sizes up to 10x10 mm2. The multilayers were optimized for specific reflectivity-to-transmission ratios for different radiation wavelengths and incident angles. The optical performance of the beam splitters was characterized by means of XUV reflection and transmission measurements and special attention was paid to the spatial homogeneity of the optical response and reflected beam wavefront distortions. The surface roughness at different spatial frequencies and flatness was studied by means of atomic force microcopy and optical interferometry. Although possible applications of such beam splitters are numerous, we will focus on a new compact instrumental setup to perform autocorrelation experiments in order to characterise the time structure of FEL pulses. The scheme includes two complimentary techniques of autocorrelation function measurements: indirect, through the Fourier transform of the spectral intensity and a novel, direct technique by means of multilayer-based Fabry-Pérot interferometry, so called Cross-mode Linear Interferometry (CLI). The setup contains two closely-spaced multilayer beam splitters. In addition, the extension of multilayer beam splitters from the XUV regime to soft X-rays will be discussed.

8078-14, Session 4

Multilayer mirrors for FERMI@ELETTRA beam transport system

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Experiments performed in a Free Electron Laser (FEL) facility can require a selection of higher harmonics; a typical example is the pump and probe experiments in which the system under test is pumped with a fundamental wavelength and probed with its third harmonic. The wavelengths selection performed by a monochromator can affect beam properties such as wavefront deformation or time elongation and its usage in the beam manipulations should be avoided, expecially for High Gain Harmonic Generation (HGHG) seeding scheme. Nevertheless, for a limited number of wavelengths, the selection can be performed using periodic multilayer coatings (MLs) with the reflectivity peak tuned at the desired harmonic: this technique is already foreseen at the new FERMI@Elettra FEL facility for selecting 20nm, 16nm, 13.5nm and 6.66nm harmonics. In order to improve the fundamental rejection, the MLs have been overcoated by different capping-layers. Good results have been obtained at the shortest wavelengths using a capping-layer based on an third absorbent material. However, this approach has not showed considerable improvements at the longest wavelengths and an interferential aperiodic capping-layers designed using a method based on the control of standing wave distribution have been investigated. In this work are presented the MLs design proposed for the FERMI@Elettra FEL beam transport system.

8078-15, Session 4

Development of X-ray optics for advanced research light sources

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X-ray mirrors are needed for beam guidance, beam alignment and monochromatisation at advanced research light sources, for instance FLASH, European XFEL and PETRA III. At the Helmholtz-Zentrum Geesthacht (formerly GKSS), an in-house designed magnetron sputtering facility for the deposition of single and multilayers has been installed for the development of X-ray optics. Earlier results showed that the fabrication of 1.5 m long amorphous carbon coatings was very successful. These single layers are currently used as total reflection mirrors at FLASH to guide the photon beam to the various beamlines. A major advantage of the sputtering facility is that it is now possible to

prepare one, two or more mirrors with similar properties over the whole deposition length. In this contribution we present results of the X-ray optical properties of various mirrors, especially single C, B4C layer and W/C multilayers.

The goal of the development of X-ray mirrors is to optimize the deposition conditions in order to achieve high reflectivity and to control the thickness of the single layer or the lateral period of the multilayer over the whole deposition length according to the application. A constant period of the multilayer is required for a double-multilayer monochromator. A laterally graded multilayer mirror is interesting for focusing applications. The quality of the multilayer stack and the variation in multilayer period were precisely investigated. The properties of the X-ray mirrors were determined by means of X-ray reflectometry, transmission electron microscopy and interference microscopy. Their performance was analyzed over the whole deposition length, considering X-ray reflectivity, film thickness, micro-roughness and the uniformity of these properties. The results will be discussed and compared with former results.

8078-27, Poster Session

Visualizing XUV-induced isomerisation of acetylene cations in the free electron laser field

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Ultrafast isomerisation of acetylene cations in the low-lying excited state, populated by the absorption of XUV photons (38 eV), has been observed at the Free electron LASer at Hamburg, FLASH. Recording coincident fragments C^+ + CH_2^+ as a function of time between XUV-pump and -probe pulses, generated by a split-mirror device, we find an isomerisation time of 52 fs in a kinetic energy release (KER) window of 5.8 eV < KER < 8 eV, providing clear evidence for the existence of a fast, non-radiative decay channel.

8078-28, Poster Session

Ion imaging experiments at FLASH, LCLS, and SCSS

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Results and conclusions drawn from various ion (and electron) imaging experiments performed at the three VUV and X-ray FELs currently in operation - FLASH, SCSS, and LCLS - will be presented. These include in particular pump-probe experiments on laser-aligned molecules performed with a double velocity map imaging (VMI) spectrometer at LCLS and ion-ion coincidence and electron-ion coincidence experiments using a reaction microscope (REMI) setup at FLASH, SCSS, and LCLS.

In the former, diiodobenzene and dibromobenzene molecules were adiabatically aligned with a nanosecond IR-laser and the alignment was probed with the FEL pulse by means of ion imaging. In addition, the molecules were dissociated by a femtosecond IR-laser prior to the FEL pulse and ion and photoelectron images were recorded for various delays between IR-laser and FEL.

The reaction microscope experiments range from coincidence experiments on various small and medium-sized molecules to VUV-pump-VUV-probe experiments performed at FLASH and SCSS with a split-mirror refocusing setup. These pump-probe experiments image directly the nuclear dynamics in photo-excited molecules and allow following chemical reactions such as isomerisations in real-time. In addition, they provide a means to perform autocorrelation experiments and to thus determine the FEL pulse length and coherence time.

Based on our experiences at the three FEL facilities, a comparative analysis on the particular strengths and weaknesses of each machine for ion imaging experiments (e.g. with regards to the pulse patterns and repetition rates) will be attempted to conclude the presentation.

8078-30, Poster Session

Practical experience from operating the imaging pnCCD detectors of the CAMP chamber at LCLS

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The Max-Planck Advanced Study Group (ASG) within the Center for Free Electron Laser Science (CFEL) has built the CFEL-ASG MultiPurpose (CAMP) chamber, which provides a unique combination of particle and photon detectors, for experiments at 4th generation light sources. In particular, CAMP includes two sets of newly developed 1024 * 1024 pixel pnCCD imaging detector systems. The CAMP chamber has now been successfully employed during the first two beamtimes at LCLS, and we report here on practical experience gained for the operation of imaging pnCCD detectors at FEL facilities. We address a wide range of topics: the effect of accidental direct exposure of a CCD to the focused and unattenuated X-ray beam; effects of accidental direct impact on the CCDs of high speed particles generated by the FEL beam impinging the experimental setup; contamination of the CCD entrance window with sample material; CCD energy calibration during experiments; suppression of optical light contamination in pump-probe experiments; and CCD radiation damage from the intense photon signals. These lessons learned will help us to further improve operation of pnCCDs in future FEL experiments.

8078-31, Poster Session

Calibration methods and performance evaluation for pnCCDs in experiments with FEL radiation

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During measurement campaigns of the Max-Planck Advanced Study Group (ASG) in cooperation with the Center for Free Electron Laser Science (CFEL) at DESY-FLASH and SLAC-LCLS, pnCCDs have been established as universal photon imaging spectrometers in the energy range from 90 eV to 2 keV. In the CFEL-ASG multi purpose chamber (CAMP), pnCCD detector modules are an integral part of the design with the ability to detect photons at very small scattering angles. In order to fully exploit the spectroscopic and intensity imaging capability of pnCCDs, it is essentially important to translate the unprocessed

raw data into units of photon counts for any given position on the detection area.

We have studied the performance of pnCCDs in FEL experiments and laboratory test setups for the range of signal intensities from a few X-ray photons per signal frame to 100 or more photons with an energy of 2 keV per pixel. Based on these measurement results, we were able to characterize the response of pnCCDs over the experimentally relevant photon energy and intensity range. The obtained calibration results are directly relevant for the physics data analysis. The accumulated knowledge of the detector performance was implemented in guidelines for detector calibration methods which are suitable for the specific requirements in photon science experiments at Free Electron Lasers.

We discuss the achieveable accuracy of photon energy and photon count measurements before and after the application of calibration data. Charge spreading due to illumination of small spots with high photon rates is discussed with respect to the charge handling capacity of a pixel and the effect of the charge spreding process on the resulting signal patterns.

8078-32, Poster Session

Large format imaging detectors for X-ray free-electron-lasers

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New generation synchrotron light sources, the X-ray free electron lasers, require a two dimensional focal plane instrumentation to perform X-ray imaging from below 100eV up to 25keV. The instruments have to face the accelerator bunch structure and energy bandwidth which is different for existing (FLASH, Hamburg) and future photon sources (LCLS, Menlo Park, SCSS, Hyogo and XFEL, Hamburg). Within the frame of the Center for Free Electron Laser Science (CFEL), a joint effort of the Max-Planck Society, DESY and the University of Hamburg, the MPI semiconductor laboratory developed and produced large area X-ray CCD detectors with a format of nearly 60cm2 image area. They show outstanding characteristics: a high readout speed due to a complete parallel signal processing, high and homogeneous quantum efficiency, low signal noise, radiation hardness and a high pixel charge handling capacitance.

We will present experimental results which demonstrate the X-ray spectroscopic and imaging capabilities of the fabricated devices. We will also report on the concept and the anticipated properties of the full, large scale system. The implementation of the detector into an experimental chamber (CAMP: CFEL-ASG multi-purpose chamber) to perform measurements e.g. of macromolecules in order to determine their structure at atomic resolutions, will be shown.

8078-33, Poster Session

Characterization of the FERMI@Elettra's on-line energy spectrometer

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FERMI@Elettra is a Free Electron Laser (FEL) under construction at Sincrotrone Trieste in Italy. It will provide a fully coherent, transform limited radiation with a very high brilliance in the VUV/Soft X-ray range.

The first part of the photon transport system, aimed to deliver the radiation into the experimental chambers, is dedicated to the beam diagnostic. This section, called PADReS (Photon Analysis, Delivery and Reduction System) includes the Beam Defining Apertures, Beam Position Monitors, Intensity Monitors, Photon Energy Spectrometer, and the transversal coherence measurement system. All the diagnostic will be non-invasive and shot-to-shot, with the only exception of the transversal coherence measurement. Among these, the photon energy spectrometer is an essential instrument to aid the machine physicist to properly set up the insertion devices as well as to characterize with sub-meV resolution the photon pulses energy distribution during experiments.

After a short description of the whole photon transport system we will describe the working principle of Variable Line Spacing (VLS) diffraction gratings, and its application to the spectrometer.

The design concept of the optical system, and the supporting ray tracing and efficiency simulations will be reported.

The involved optics have also been characterized at various spatial frequencies with several metrology instruments: Long Trace Profiler (LTP), White-Light Interferometer, Atomic Force Microscope (AFM); the results of this characterization will be presented. The engineering constraints and the necessary manufacturers' tolerances will be discussed in detail. The results of the first characterization with FEL radiation will be shown, along with a comparison with simulations.

8078-34, Poster Session

Delay systems and phase retarders based on multilayers coated mirrors for FEL beam manipulation

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The intensity of the radiation produced by a Free Electron Laser (FEL) is more intense, coherent, and with much higher photon density with respect to the radiation generated by storage rings undulators. FERMI@Elettra will use a "seeding technique" which provides near Gaussian temporal structures with a bandwidths close to the transform limit. In order to preserve the properties of such pulse, the beam manipulation towards the ending station is performed by the use of multilayer coatings (MLs). The primary application is the delay line system, useful in pump and probe experiment: the beam is split and one of the arm is equipped with multilayer mirrors which are able to reject the fundamental one; the delay of few nanosecond can be controlled by changing the mirrors distance. Specific design and working principle of such MLs are presented elsewhere. In this work the time delay of pulse travelling in the nanostructures is investigated and photoemission experiment applied to its evaluation conceived. Mirrors alignment effects on polarization and group velocity have been evaluated in a full delay line configuration. In the same time, MLs are also studied for verifying their possible application in a phase shifter set-up, useful to have control of the source polarization or to produce elliptical and circularly polarized light. In this way, the FELs circular polarized radiation, which is emitted out of the electron plane and therefore it is very difficult to be manipulated, can be generated also from a plane pulse linearly polarized.

8078-35, Poster Session

Partial-coherence colored-noise approach to model FEL pulse statistics

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No abstract available

8078-16, Session 5

Determination of temporal FEL pulse properties: challenging concepts and experiments

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One of the most challenging tasks for the FEL photon diagnostics is the precise determination of the FEL pulse duration or even getting information on the substructure of the SASE pulses.

The knowledge of the temporal pulse characteristics is not only important for nonlinear interactions which rely purely on the correct determination of the intensity, but also to gain insight on the dynamics of the investigated processes. Here, the resolution of pump-probe experiments relies heavily on knowledge of the pulse duration for one color pump-probe and in addition on the precise arival time difference for 2-color pump probe experiments.

Due to the wide range of available parameters at the existing and planed - photon energies ranging from VUV to X-rays with pulse durations of few fs or even sub fs range up to pulses with several 100 fs pulse duration - a variety of methodes has to be investigated and utilized in order to characterize the temporal structure of these pulses. Moreover due to the statistical nature of the SASE process the pulse shape (consisting of few up to hundreds of sub pulses) varies pulse by pulse. Here, techniques to characterize the pulse shot by shot - increasing the level of complexity in contrast to averaging techniqhes by far - are needed.

The talk will provide an overview of various concepts how to measure the pulse duration for VUV to X-rays focussing on the range of application, the strength and weaknesses for the different approaches. Finaly, results of several experimental campaigns characterizing the temporal shape of the FEL pulses at FLASH and LCLS will be presented.

8078-17, Session 5

First results from the commissioning of the FERMI@Elettra free electron laser by means of the Photon Analysis Delivery and Reduction System (PADReS)

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The Italian Free Electron Laser (FEL) facility FERMI@Elettra has started to produce photon radiation at the end of 2010. The photon beam is presently delivered by the first undulator chain (FEL1) that is supposed to produce photons in the 80-20 nm wavelength range. A second undulator chain (FEL2) will be commissioned at the end of 2011, and it will produce radiation in the 20-3nm range.

The Photon Analysis Delivery and Reduction System (PADReS) was designed to collect the radiation coming from both the undulator chains (FEL1 and FEL2), to characterize and control it, and to redirect it towards the following beamlines.

The first parameters that are checked are the pulse-resolved intensity and beam position. For each of these parameters two dedicated monitors are installed along PADReS on each FEL line. In this way it possible to determine the intensity reduction that is realized by the gas reduction system, which is capable of cutting the intensity by up to four orders of magnitude.

The energy distribution of each single pulse is characterized by an online spectrometer installed in the experimental hall. Taking advantage of a variable line-spacing grating it can direct the almost-full beam to the beamlines, while it uses a small fraction of the beam itself to determine the spectral distribution of each pulse delivered by the FEL.

The transversal coherence of the FEL photon beam is then measured and characterized using a simple experimental setup based on the diffraction from a double slit. Different slit dimensions and spacings are used to fully determine the coherence from the reading of the fringe visibility that is performed on a YAG crystal imaged by a CCD camera.

The first light of FERMI@Elettra, delivered to the PADReS section in late 2010, is used for the first commissioning runs and some preliminary experiments whose the results are reported and discussed in detail.

8078-18, Session 5

Hard X-FEL source diagnostics at LCLS using a grating interferometer

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X-ray grating interferometry is a method for differential X-ray phase measurements that has been deployed at several synchrotron sources. It is based on a phase shifting beam splitter and an absorbing analyzer grating. The small grating periods of only a few micrometers result in a very high sensitivity to record the local propagation direction of an X-ray wave front. As the interferometer is capable of recording the wave front of a single laser pulse, it has also provided insight into the effects of the accelerator and undulator settings on the LCLS wave front on a shot-to-shot basis. These properties make grating interferometry highly interesting for the investigation of XFEL sources.

We report on recent source diagnostics experiments from the hard X-Ray at the LCLS X-Ray Pump Probe (XPP) endstation. The extreme flexibility of the source and the option to tune the accelerator and undulator parameters during the experiments allowed us to investigate the effects of deliberately induced longitudinal and transverse source point displacements and shot-to-shot source point fluctuations. Longitudinal displacements change the wavefront radius of curvature whereas lateral displacements modify the first derivative of the wavefront phase respectively - both of which can be measured.

Shot-to-shot fluctuations are analyzed using a moiré technique, where spatial resolution can be traded in a continuous manner for sensitivity. Using one-dimensional grating structures, this analysis can be carried out with high spatial resolution in one direction of interest, whereas the use of two-dimensional gratings allows a simultaneous measurement in two perpendicular directions at the cost of reduced spatial resolution. The technique is expected to develop into a useful diagnostics tool both for LCLS and future hard XFEL sources.

8078-19, Session 5

Beam characterization of FLASH from Hartmann data and measurement of the Wigner distribution function

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Beam parameters of the free electron laser FLASH emitting in the EUV spectral range were determined from wavefront measurements using a self supporting Hartmann sensor operating in the spectral range from 6 to 30nm. The device was applied for alignment of the ellipsoidal focusing mirror at BL2, reducing the rms wavefront aberrations by more than a factor of 3. The spot size of 31µm (horizontal) and 27µm (vertical) full-width at half maximum (FWHM) as well as other beam parameters were evaluated from wavefront and intensity data delivered by the Hartmann sensor. Furthermore, 100 two-dimensional single pulse intensity distributions were recorded at each of 40 axial positions, spaced app. ±2 Rayleigh lengths around the waist of the optimized FEL beam with a magnifying EUV sensitized CCD camera. From these beam profile data the single pulse as well as the average Wigner distribution function could be reconstructed on two dimensional orthogonal subspaces by an inverse Radon transform and proper interpolation. For separable beams this yields the complete Wigner distribution and gives comprehensive and high-resolution information on the propagation characteristics, including local Poynting vector, wavefront, mode content, mutual coherence and focusability. The wavefront of the optimized beam evaluated at waist position was in the order of /4 peak valley, whereas a significant contribution of uncorrelated higher order Hermite-Gauss modes and a global degree of coherence of 0.12 can be detected, leading to a substantial increase of the M^2 factor, which was determined to ~ 4.2 and ~ 3 in the horizontal and vertical direction, respectively. The obtained results are compared to the Hartmann experiments. Strategies for future measurement of the Wigner distribution for general beams at FLASH are discussed.

8078-20, Session 6

CAMP: a multipurpose instrument for imaging experiments and simultaneous detection of photons and charged particles at VUV and X-ray free electron lasers

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The CFEL-ASG MultiPurpose (CAMP) instrument [1] was designed and constructed by the Max Planck Advanced Study Group at CFEL to explore the interaction of intense VUV and X-ray radiation with various targets of increasing complexity and size, ranging from atoms and (laser-aligned) molecules to nano-particles such as clusters and biological targets. The apparatus is equipped with two large-area, single-photon counting pnCCD detectors and custom-designed ion and electron imaging spectrometers (e.g. a double-VMI and a reaction microscope) that can be employed together with the pnCCDs. It therefore allows measuring fluorescent or scattered photons in coincidence with ions and electrons emitted in the same ionization event.

The general layout and capabilities of the CAMP instrument will be reviewed and results from its first applications at LCLS will be presented.

[1] L. Strüder et al., Nucl. Instr. and Meth. in Phys. Res. A 614, 483 - 496 (2010).

8078-21, Session 6

Sample injection for pulsed X-ray sources

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The high intensity of free-electron lasers now allows for the possibility of obtaining measurable diffraction from biological samples with a single X-ray pulse. An important consequence of diffract-before-destroy imaging is that the sample is destroyed and therefore must be replaced preferably at the repetition rate of the FEL. This presents an interesting challenge; the sample must be rapidly replaced within the X-ray focus at the proper particle density and degree of hydration without damaging or denaturing the sample. If particle number density is too high, for example due to clustering or evaporation, the diffraction pattern resulting from coherent illumination of multiple particles may be discarded when sorting for 3D reconstruction. If number density is too low the hit rate, percentage of pulses with measurable scattered intensity, may also be too low to collect a complete data set. Evaporation will also leave behind less volatile material and this change of concentration may be damaging to the sample. On the other hand the similarity in electron density for water and biological material provides poor contrast for fully hydrated material. It is often also necessary to consider sample consumption. While high, near unity, hit rate can be obtained using liquid jets, a liquid flow rate greater then 1 microliter per minute must be maintained. Several sample injection possibilities, drop on demand, aerosols, liquid jets, aerodynamic lenses, and soapy films, have been explored and a review of these results is presented.

8078-22, Session 6

PnCCDs as high-speed imagers for X-ray and electron imaging and spectroscopy: first experience at FLASH and LCLS

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Fourth generation accelerator-based light sources, such as VUV and X-ray Free Electron Lasers (FEL), deliver ultra-brilliant (~1012-1013 photons per bunch) coherent radiation in femtosecond (~10 fs to 100 fs) pulses and, thus, require novel focal plane instrumentation in order to fully exploit their unique capabilities. As an additional challenge for detection devices, existing (FLASH, Hamburg, LCLS, Menlo Park) and future FELs (SCSS, Hyogo and XFEL, Hamburg) cover a broad range of photon energies from the EUV to the X-ray regime with significantly different bandwidths and pulse structures reaching up to MHz micro-bunch repetition rates.

We will report on our experience of large format pnCCDs integrated in the experimental end-station CAMP (CFEL-ASG Multi Purpose) at experiments at FLASH and LCLS. As the spectrum of experiments is extremely wide the detection system has to be as flexible as possible. We have covered an energy bandwidth from 30 eV up to 17.5 keV, a frame rate from 5 Hz up to 120 Hz, spectroscopy with single photons as well as imaging with several thousand photons in one pixel. The instrument has to cope with the X-rays, with electrons and optical photons, being either part of the signal or the background. We will summarize our operational experience and highlight the requirements, specifications and achievements.

A new pnCCD camera will be presented having 4 Megapixel per focal plane compared to 1 Megapixel in the present one. In addition parameters like pixel size, charge handling capacity, frame rate, electronic noise, etc. will be discussed in the context of electrical, thermal, mechanical and geometrical constraints. The concept of a 4-side buttable system will be introduced to fill the field of view with minimum insensitive gaps in between the individual devices.

The talk will finish with a brief outlook for the 4.5 MHz Focal Plane Cameras for the European XFEL. Details about the E-XFEL detectors (DePFET Detector System with Integrated Signal Compression, DSSC) and the expected performance figures of the DSSC will be given in a separate talk.

8078-23, Session 6

Development of the DEPFET sensor with signal compression: a large format X-ray imager with mega-frame readout capability for the European XFEL

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The DSSC Consortium, headed by the MPI-Halbleiterlabor in Munich, is developing a high speed focal plane detector system, together with the related readout electronics for the new European XFEL in Hamburg. The DSSC (DEPFET Sensor with Signal Compression) instrument will be able to record X-ray images with a maximum frame rate of 4.5MHz and to achieve a high dynamic range. The system is based on a pixel-silicon sensor with a DEPFET as a central amplifier structure. The sensor will have a total size of approximately 200 × 200 um^2, composed of 1024 × 1024 pixels with hexagonal shape. The pixel array will be subdivided into 16 ladders with 128 × 512 pixels each. Every detector ladder is bump-bonded to mixed signal readout ASICs.

The ASICs are designed in 130nm technology and provide full parallel readout of the DEPFET pixels. The parallel readout is mandatory in order to cope with the high repetition rate of the XFEL machine. The signals coming from the individual pixels of the detector, after being processed by an analog filter, are immediately digitized by a series of series of 8-bit ADCs (9-bit at half of the maximum speed) and locally stored in a SRAM also integrated in the ASICs. During the 99ms time gap of cooling phase of the accelerator, the digital data are sent off the focal plane to the back-end electronics.

It is the aim of the DEPFET detector to supply a high speed focal plane camera with high spatial resolution for X-rays from 0.5 keV up to 10 keV with close to 100 % detection efficiency. The dynamic range is designed to be 10^4 photons of 1 keV per pixel, with an analog compression on the sensor level. The most exciting and challenging property is the 220 ns frame rate of the system. This goes beyond all existing instruments and requires the development of new concepts and technologies. The pixel sensor has been designed so as to combine high energy resolution at low signal charge with high dynamic range. This is motivated by the desire to be able to be sensitive to single low energy photons and at the same time to measure at other positions of the detector signals corresponding to up to 10^4 photons of 1keV. In order to fit this dynamic range into a reasonable output signal range, achieving at the same time single photon resolution, a strongly non linear characteristic is required. The new proposed DEPFET provides the required dynamic range compression at the sensor level, considerably facilitating the task of the electronics.

During the talk the key properties and the functionalities of the main building blocks of the system will be discussed together with first experimental results. A first prototype of the readout ASIC has been realized and has been tested with a standard DEPFET prototype. Measurements have shown that it is possible to obtain a total noise of about 13 electrons r.m.s. with a readout speed of 1 MHz and about 45 electrons at 5MHz. This indicates that it will be possible to achieve the targeted single photon resolution for 1keV photons at 5MHz and also for 0.5 keV photons, in case the operating speed is reduced of a small factor. A characterization of the first available non-linear DEPFET prototypes will be presented for the first time.

8078-29, Session 6

Characterization and diagnostics of fast X-ray imaging detectors for X-ray free electron laser sources

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The current development of novel fast X-ray imagers for X-ray Free Electron Laser (XFEL) radiation sources raises the need for suitable characterization tools for studying and qualifying detector performance over a wide range of injection levels.

In fact the brilliance of XFEL sources exceeds any other light source today and in some of the foreseen experiments the pixel to pixel intensity variation may reach 1:10,000. On the other side the XFEL bunch structure requires that charge collection and signal processing is completed before the next pulse hits the detector, e.g. at the European XFEL at Hamburg each pixel has to be read out in less than 220 ns. Therefore single photon resolution has to be assured and at the same time a pixel collecting 10,000 photons should still be in the range of sensitivity with no loss of position resolution or delays in collecting time. At such extreme ionization densities, however, charge transport in the detector is strongly affected by Coulomb interaction among the generated carriers with potential degradation of both the temporal resolution and spatial resolution. The non linear response of the detector-frontend system becomes also significant.

These effects can impact very differently on different detection schemes. Two case studies are considered here: a Multi Linear Silicon Drift Detector (MLSDD) with high readout speed and a pixel design based on a novel DePMOS detector-amplifier structure with strongly non-linear characteristics.

We investigated the use of mono-energetic proton bunches - produced by the 3MV Tandetron at LABeC, Firenze, Italy - as an attractive alternative to probe the response of the detector-frontend system over a wide range of charge levels. Accelerated protons owing to their limited range in silicon can deliver precisely calibrated amount of charge along a track well matched to the typical silicon wafer with high spatial and temporal resolution. By tuning the proton energy or by increasing the number of protons per bunch it is possible to probe different levels of charge density and/or different ionization profiles across the detector depth. Deconvolution methods can also be applied to the detector output waveforms in order to gain deeper insight on detector behavior.

This work will discuss the potential of proton beams as a diagnostic tool for mapping the response of the detector-frontend system in charge, time and space at high resolution, highlighting the main design issues of the considered X-ray imaging detectors.

8078-24, Session 7

Echo-enabled harmonic generation for seeded FELs

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In the x-ray wavelengths, the two leading FEL concepts are the self-amplified spontaneous emission (SASE) configuration and the high-gain harmonic generation (HGHG) scheme. While the radiation from a SASE FEL is coherent transversely, it typically has rather limited temporal coherence because the SASE FEL starts from the shot noise. Alternatively, the HGHG scheme allows the generation of fully coherent radiation by up-converting the frequency of a high-power seed laser. However, due to the relatively low up-frequency conversion efficiency, multiple stages of HGHG FEL are needed in order to generate x-rays from a UV laser. The up-frequency conversion efficiency can be greatly improved with the recently proposed echo-enabled harmonic generation (EEHG) technique. The EEHG FEL uses two modulators in combination with two dispersion sections to generate a high-harmonic density modulation starting with a relatively small initial energy modulation of the beam. The main advantage of EEHG is that the bunching factor is a slowly decaying function of the harmonic number, thus allowing the generation of coherent soft x-ray radiation directly from a UV seed laser in a single stage. The remarkable up-frequency conversion efficiency of the EEHG technique has stimulated world-wide interest in using EEHG. While significantly relaxing the requirements on laser power and beam slice energy spread as compared to the HGHG scheme, EEHG requires more challenging control of the beam dynamics.

In this work we will present the concept of EEHG, and address some practically important issues, such as the effect of coherent and incoherent synchrotron radiation, that affect the performance of the seeding. Using a realistic set of beam parameters of several current soft x-ray projects and proposals, we show how the EEHG scheme can be incorporated in them and what is the expected performance of the seeded FELs. We will also discuss application of the echo modulation for generation of atto-second pulses of radiation, and a feasibility of the EEHG in the LCLS-II upgrade.

We will then describe the first proof-of-principle experiment on EEHG carried out at the Next Linear Collider Test Accelerator (NLCTA) at SLAC. We will review the experimental results, discuss some challenges and present future plans for this experiment.

8078-25, Session 7

Self-seeding schemes for the European XFEL

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Typical SASE XFEL pulses exhibit poor longitudinal coherence, a characteristic inherited from the start-up from shot noise. Self-seeding schemes are an answer to the call for improved longitudinal coherence. If applied to already working or designed XFELs, these schemes are subject to constraints, including minimal change to the baseline design, and possibility to recover the baseline mode of operation. Recently, a novel single-bunch self-seeding scheme was proposed, based on a particular kind of monochromator, which relies on the use of a single crystal in Bragg-transmission geometry.

In its simplest configuration, the self-seeded XFEL consists of an input undulator and an output undulator separated by such monochromator. The input undulator operates in the linear high-gain regime starting from the shot-noise in the electron beam. After the first undulator, the output SASE radiation passes through the monochromator, which reduces the bandwidth to the desired value. According our scheme, the SASE pulse coming from the first undulator impinges on a crystal set for Bragg diffraction. Then, the single crystal in Bragg geometry actually operates as a bandstop filter for the transmitted X-ray SASE radiation pulse. When the incident angle and the spectral contents of the incoming beam satisfy the Bragg diffraction condition, the temporal waveform of the transmitted radiation pulse shows a long monochromatic tail, whose duration is inversely proportional to the bandwidth of the absorption line in the transmittance spectrum. While the radiation is sent through the crystal, the electron beam passes through a magnetic chicane, which accomplishes three tasks by itself: it creates an offset for the crystal installation, it removes the electron micro-bunching produced in the first undulator, and it acts as a delay line for the implementation of a temporal windowing process. In other words, the magnetic chicane shifts the electron bunch on top of the monochromatic wake created by the bandstop filter thus selecting (temporal windowing) a part of the wake. By this, the electron bunch is seeded with a radiation pulse characterized by a bandwidth much narrower than the natural FEL bandwidth.

In some experimental situations this simplest two-undulator configuration is not optimal. The obvious and technically possible extension is to use a setup with three or more undulators separated by monochromators. This amplification-monochromatization cascade scheme is distinguished, in performance, by a small heat-loading of crystals and a high spectral purity of the output radiation, and is particularly advantageous for the European XFEL. The power of the output signal can be further increased by tapering the magnetic field of the undulator. Once the cascade self-seeding scheme is combined with tapering in a tunable-gap baseline undulator at the European XFEL, a source of coherent radiation with unprecedented characteristics can be obtained at hard X-ray wavelengths, promising complete longitudinal and transverse coherence, and a peak brightness three orders of magnitude higher than what is presently available at LCLS. Additionally, the new source will generate hard X-ray beams at extraordinary peak (TW) and average (kW) power level. The proposed source can thus revolutionize fields like single biomolecule imaging, inelastic scattering and nuclear resonant scattering. Our self-seeding scheme is extremely compact, and takes almost no cost and time to be implemented. The upgrade proposed in this work could take place during the commissioning stage of the European XFEL, opening a vast new range of applications from the very beginning of operations. We present feasibility study and exemplifications for the SASE2 line of the European XFEL.

8078-26, Session 7

Development of optical cavities for hard X-ray FEL oscillators

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Free-electron lasers for hard x-rays can be constructed in oscillator (XFELO) configuration, providing ultra-high spectral purity and brightness [1]. The average brightness is expected to be several orders of magnitude higher than, and peak brightness comparable to that of SASE XFELs. XFELOs can enable revolutionary scientific opportunities as well as drastically improve experimental techniques developed at third-generation x-ray facilities.

Low-loss x-ray crystal cavity and ultra-low-emittance electron beams are two major technical challenges in the realization of XFELOs. The requirements to the x-ray cavity components are demanding: diamond crystals and curved grazing incidence mirrors must have near-perfect reflectivity, negligible wave-front distortions, and subject to very tight tolerances on the angular, spatial, and thermal stability under high heat load of the XFELO radiation. This paper gives an overview on the recent progress [2-4] and future plans in the R&D on the feasibility of x-ray cavities for XFELOs. The experimental and simulation studies results provide strong evidence for the feasibility of x-ray cavities.

1. K-J. Kim, Yu. Shvyd'ko, S. Reiche, PRL 100 (2008) 244802

2. Yu. Shvyd'ko, et al, Nature Phys. 6 (2010) 196

3. S. Stoupin, Yu. Shvyd'ko, PRL 104 (2010) 085901

4. S. Stoupin et al, Rev. Sci. Instr. 81 (2010) 055108

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Conference 8079A: Laser Acceleration of Electrons, Protons and Ions

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8079A-01, Session 1

Tunable two-stage laser-plasma accelerator based on longitudinal density tailoring

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The high acceleration gradient in laser-driven plasma accelerators (LPAs) has allowed for the production of compact devices delivering high-quality electron beams with GeV energies from acceleration over centimeter length scales. LPAs have been considered for driving modules of future high energy colliders, and hyper-spectral light sources capable of delivering intrinsically synchronized femtosecond beams of electrons and light pulses, with frequency ranging from THz to gamma ray. These applications require a high degree of stability, beam quality, and tunability. Similar to the implementation of conventional accelerators, here we report on the generation of such beams from a laser plasma accelerator using separate injection and acceleration modules. This two-stage approach relies on a longitudinally tailored plasma density profile and has allowed for the generation of stable beams with energies tunable in the range of 100 to 400 MeV. Work supported by US DOE Contract No. DE-AC02-05CH11231.

8079A-02, Session 1

Narrow energy spread electron beams from the ALPHA-X laser wakefield accelerator

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The Advanced Laser-Plasma High-Energy Accelerators towards X-rays (ALPHA-X) programme is developing laser-plasma accelerators for the production of ultra-short electron bunches with subsequent generation of coherent short-wavelength radiation pulses in a free-electron laser (FEL). As well as for injection into accelerators or FELs, as in the case of this project, ultra-short electron bunches have numerous direct applications such as in ultrafast electron microscopy or time-resolved electron diffraction. Ultra-short radiation pulses generated in these compact sources will also be of tremendous benefit for time-resolved studies in a wide range of applications across many branches of science.

Here we report on the latest laser wakefield accelerator experiments on the University of Strathclyde ALPHA-X accelerator beam line looking at narrow energy spread electron beams. ALPHA-X uses a 26 TW Ti:sapphire laser (energy 900 mJ, duration 35 fs) focused into a helium gas jet (nozzle length 2 mm) to generate high quality monoenergetic electron beams with central energy in the range 80-180 MeV. The beam is fully characterised in terms of the charge, transverse emittance, energy spread and bunch length. In particular, the energy spectrum (with less than 1% measured energy spread) is obtained using a high resolution magnetic dipole imaging spectrometer and the latest observations will be presented, with implications for applications discussed.

8079A-03, Session 1

Evolution of electron-bunch parameters during laser-wakefield acceleration

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In several proof-of-principle experiments it has been demonstrated that laser-wakefield acceleration of relativistic electrons could be a promising complement to conventional accelerator systems for certain applications. Despite major improvements of the beam quality over the last years, laser-accelerated electron bunches still have not reached the parameters and controllability eventually indispensable for their employment in e.g. X-ray generation.

In the presented work the evolution of the electron bunch properties during the acceleration process is studied experimentally and in simulation. The 25 fs, 2 Joules pulses of the upgraded ATLAS laser are focused into a steady-state flow gas cell. As already demonstrated, the combination of a very reproducible and turbulence-free gas target and a stable laser system allows for stable acceleration of electron bunches. The new possibility to continuously change the acceleration distance by changing the length of the gas cell provides an additional means to optimize - and to a certain degree even control - the final electron beam parameters. Furthermore, the bunch can be extracted in different phases of the acceleration process, which helps to gain better insight into the underlying physics. The length after which the relativistic electrons outrun the accelerating phase of the electric field and are decelerated again, the so-called dephasing length, was determined for different electron densities. Dephasing length and the deducted strength of the accelerating electric field are compared to theory. Peak energy, energy spread, charge and divergence of the electron bunch at different stages of the acceleration process were extracted and compared to full-scale three-dimensional particle-in-cell simulations.

8079A-04, Session 1

Plasma wave structure and particle trapping in nonlinear laser wakefields

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We investigate the excitation of nonlinear plasma waves (including the blow-out and bubble regimes) formed by an ultra-short ($k_p L \sim 2$), intense ($a > 2$) laser pulse interacting with an underdense plasma. A detailed examination of particle orbits and wakefield structure is performed using reduced analytical models and numerical simulations with the 2D cylindrical, envelope, ponderomotive, hybrid PIC/fluid code INF&RNO, recently developed at LBNL. In particular we study the requirements for injection and/or trapping of background plasma electrons in the nonlinear wake. Characterization of the phase-space properties of the injected particle bunch is also discussed. Work supported by US DOE Contract No. DE-AC02-05CH11231.

8079A-05, Session 2

Complete characterization of laser wakefield acceleration

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Laser-driven electron acceleration utilizing plasma waves (the so called laser wakefield acceleration, LWFA) has been proven to generate ultra-relativistic (up to the GeV range), quasi-monoenergetic (down to 1% energy spread) electron bunches with orders of magnitude higher electric fields (100s of GV/m) and much shorter electron pulses (few fs) than state-of-the-art radiofrequency accelerators (100 MV/m, ps to ns duration). Although, measurement of the various properties of the electrons is essential for various applications a complete characterization of the LWFA electron sources, in contrast to the radiofrequency sources, is still lacking. The various techniques to obtain the main properties in conventional accelerators as charge, spectrum, normalized emittance, spatial and temporal structure of the bunches or the accelerating field and structure are not always adaptable to LWFA. This is due to significant differences in the values of some properties. Therefore, a combination established and novel methods are required for a complete characterization that we discuss in the paper. Furthermore, we report on a detailed measurement of the accelerated electron bunches and the acceleration process itself. We apply an 8 fs long optical parametric chirped pulse amplifier system to generate electrons with 20-30 MeV energy in supersonic He gas jets of ~1019 cm-3 plasma density. Measurements of the most important properties with this system will be discussed. However, the applied techniques are suitable to lasers with longer pulse duration as well. Future applications, such as the development of laboratory X-ray sources with unprecedented peak brilliance or ultrafast time-resolved measurements critically rely on a complete characterization of the acceleration process and the electron bunch.

8079A-06, Session 2

Measurement of the transverse electron beam size right after exiting the capillary of a laser-plasma accelerator

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Laser-wakefield acceleration is maturing into a stable source of ultra-relativistic electron beams. We show experimental data of the imaging of these novel beams after their generation by using miniature magnetic quadrupole lenses. These devices address the main challenges of high divergence and pointing fluctuations of several mrad while still maintaining the intrinsic advantages of ultra-short pulse duration and low transverse emittance. In particular, we can use electron beam imaging in order to magnify and measure the electron beam source size directly after the exit of the accelerator. Studying the source size as a function of experimental parameters such as the plasma density or acceleration length can give insights into the acceleration process and be used to quantify the beam emittance.

8079A-07, Session 2

In-situ on-axis density characterization of plasma channels based on two-color group velocity dispersion

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Laser-plasma accelerators (LPAs) have demonstrated high-quality GeV electron beams using a cm-scale capillary plasma channel (density ~1e18 cm-3) and a relativistic laser pulse (intensity >1e18 W cm-2).

Knowledge of the plasma density is of critical importance to LPA physics. Traditional time-resolved plasma diagnostics (such as transverse or longitudinal density interferometry) rely on phase reconstruction of a probe laser pulse. Unfortunately, the cylindrical capillary geometry, the intrinsic roughness of the capillary walls, and the small capillary diameter make such techniques challenging to apply. Here, we demonstrate a novel diagnostic that measures the averaged on-axis plasma channel density. The technique relies on the density-dependent difference in group velocity of two probe pulses of different central wavelengths (800 nm and 400 nm). By measuring the change in arrival time of both pulses with an optical spectrometer we can reconstruct the plasma density. We have compared our results to other experimental methods as well as to gas flow simulations. The single-shot in-situ nature of this technique allows for rapid exploration of capillary discharge parameters such as capillary backing pressure, discharge voltage, and discharge timing. Work supported by US DOE Contract No. DE-AC02-05CH11231.

8079A-08, Session 2

High-resolution emittance and energy spread measurements of relativistic electron beam from laser wakefield accelerator

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The normalised transverse emittance is a measure of the quality of an electron beam generated from a laser-plasma wakefield accelerator (LWFA). The brightness, parallelism and focusability are all functions of the emittance. Here we present a high-resolution single shot method of measuring the transverse emittance of a 125 MeV electron beam generated from a LWFA using a pepper-pot mask. An average normalised emittance of around εrms,x,y=2.0 ± 0.6 pi-mm-mrad was measured, which is comparable to that of a conventional accelerator. The best measured emittance was εrms,x=1.1 ± 0.1 pi-mm-mrad, corresponding to the resolution limit of our system. We also obtained high energy monoenergetic electron beam with a relative energy spread less than 0.8% (without deconvolution). The low emittance and energy spread indicate that our accelerator is suitable for driving a compact free electron laser.

8079A-09, Session 3

The transparent overdense regime of plasma physics: experimental demonstration of high efficiency particle acceleration, coherent photon generation, and relativistic pulse shaping

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The constantly improving capabilities of ultra-high power lasers are enabling interactions of matter with ever extremer fields. As both the on target intensity and the laser contrast are increasing, new physics regime are becoming accessible and new effects materialize which in turn enable a host of applications. A first example is the realization of interactions in the transperent-overdense regime (TOR), which is reached by interacting a highly relativistic (a0>10), ultra high contrast laser pulse with a solid density, nanometer target. Here, a still overdense target is turned transperent to the laser by the relativistic mass increase of the electrons, increasing the skin depth beyond the target thickness and thus enabling volumetric interaction of the laser with the entire target instead of only a small in-teraction region at the critical density surface. This increases the energy coupling, enabling a range of effects, including relativistic optics and pulase shaping, mono-

energetic electron acceleration, highly efficient ion acceleration in the break-out afterburner regime, the generation of relativistic and forward directed surface harmonics. In this talk we will show the theoretical framework for this regime, explo-red by multi-D, high resolution and high density PIC simulations as well as analytic theory [6] and present measurements and experimental demonstrations of direct relativistic optics, relativistig HHG, electron acceleration, and Break-Out Afterburner (BOA) ion acceleration in the transperent overdense regime. These effects can in turn be used in a host of applications including laser pulse shaping, ICF diagnostics, coherent x-ray sources, and ion sources for fast ignition (IFI), homeland security applica-tions and medical therapy. In particular, we demonstrate acceleration of carbon ions to >0.5 GeV with a conversion efficiency of >10% for ions >20 MeV and monoenergetic carbon ions with an energy spread of 1-20%, demonstrating 3 out of for key requirements for ion fast ignition. Furthermore, the nanofoil target interactions produce ~40 MeV nC mono-energetic electrons, forward-directed relativi-stic surface harmonics and provide pulse shaping beyond the Fourier limit of the incident pulse. This host of applications already makes transperent-overdense regime one of general interest, a situation reinforced by the fact that the TOR target undergoes an extremely wide HEDP parameter space during interaction ranging from WDM conditions (e.g. brown dwarfs) early in the interaction to extremely high energy densities of ~1011 J/cm3 at peak, dropping back to the underdense but extremely hot para-meter range of gamma-ray bursts. Furthermore, whereas today this regime can only be accessed on very few dedicated facilities, employing special targets and pulse cleaning technology, the next gene-ration of laser facilities like RAL-10PW, ELI, or Gekko-Exa will operate in this regime by default, turning its understanding in a necessity rather than a curiosity.

8079A-10, Session 3

The laser-driven proton acceleration experiments at JAEA

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Because of the peculiar characteristics of the laser-driven proton beam, many potential applications are proposed including establishing compact medical accelerator for the cancer therapy. For our final destination to establish the compact laser-driven proton accelerator, the experiments are performed to investigate proton and ion acceleration from thin foil targets, using a high contrast, ultra-short laser pulse from the J-KAREN laser at the Japan Atomic Energy Agency. The P-polarized laser pulse with the parameters of 800nm, 40fs, 4J, and with extremely high ASE contrast of 1011 is focused onto the thin-foil targets with variable materials and thicknesses ranging from 100um to sub-um. The achieved peak intensity is >1020Wcm-2. The maximum proton energy is reached to 14MeV. The number of ~10MeV protons is enough to carry 2Gy dose onto the skin of the mouse within 10min with 10Hz operation. This enables us to carry out in-vivo test instead of in-vitro test. The upgrade of our beam-line is now going on to enhance the beam transport efficiency as well as employing large optics with better quality to make the wave front distortion as little as possible for realizing the laser irradiation on the target with >1021 Wcm-2 intensity. Progresses on the proton acceleration experiments from the upgrade are also shown.

8079A-11, Session 3

Progress in optimizing laser-generated ion beams

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In the exploration of the ultimate limits in laser - ion acceleration considerable effort is spent on maximizing the light-to-particle-energy conversion efficiency which is needed to bring laser - ion acceleration to application.

We present experiments on ion acceleration from ultra-thin diamond-like carbon (DLC) foils with thicknesses below the skin depth, irradiated by ultra-high contrast laser pulses focussed to peak intensities of 5x10^19 W/cm^2.

A significant increase of the obtained ion energies and the conversion efficiency was observed [1]. We attribute this advancement to an improved matching of the group velocities of photons, electrons and subsequently that of the ions. Specifically, this lead to an acceleration of carbon C^6+ ions dominated by the laser radiation pressure when the laser polarization was changed from linear to circular [2].

Moreover, in the same experimental setup we studied the high harmonic radiation in transmittance of the target.

The observation of the harmonics spectra allows a non-invasive extraction of the target density which is of utmost interest for the optimization of the ion acceleration process[3].

References:

[1] S. Steinke et al., Laser and Particle Beams 28, 215 (2010).

[2] A. Henig et al., Physical Review Letters 103, 245003 (2009).

[3] R. Hörlein et al., submitted, http://arxiv.org/abs/1009.1582 (2010).

8079A-12, Session 3

Energy scaling of laser accelerated protons and proton emission from reduced mass targets

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In the last years, high power laser systems in the 100 TW range with ultrashort pulses (~30 fs) and repetition rates of up to 10 Hz have come into operation. In order to investigate the laser proton acceleration in this laser regime we have performed a series of experiments using plain few-micron-thick metal targets and mass-limited silicon and gold targets. The targets were irradiated with 30 fs pulses from the new 150 TW DRACO Laser facility at the Forschungszentrum Dresden-Rossendorf which show a contrast level of 10-10 in the picosecond and 10-9 up to 10-10 in the nanosecond range.

For both target types, proton spectra have been measured with a magnetic spectrometer and radiochromic film stacks. In addition, two magnetic electron spectrometers at different angles have yielded information on the electrons emitted from the non-irradiated target rear side.

Using plain metal foil targets, we have observed a linear scaling of the maximum proton energy with laser power and could show that this behaviour is explained consistently by Schreiber's analytical scaling model [1] in the limiting case of ultrashort laser pulses [2]. Despite the high laser contrast we have found that a slight deformation of the target rear side results in a predictable deflection of the emission of energetic protons away from the target normal direction [2].

The mass limited targets tested in the experiment were silicon and gold foils with lateral sizes ranging from 20 µm to 100 µm mounted on tiny stalks. For the silicon targets, the target thickness of 2 μm corresponded to the optimum target thickness for proton acceleration at DRACO. Depending on the size of the targets strong influences of the stalks as well as the target edges were found which could both increase or decrease the maximum proton energy in comparison to a plain foil. For the gold targets which were tested for target thicknesses of 1μm and 400 nm we found an increased proton flux for the reduced mass target geometry compared to a plain foil target.

[1] J. Schreiber et al., PRL 97, 045005 (2006)

[2] K. Zeil et al., NJP 12, 045015 (2010)

8079A-13, Session 3

Control of proton beam spectra from high intensity, high contrast laser interactions

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Experiments and simulations were performed on the ability to shape proton spectra by means of careful control over laser contrast and intensity. Up to 50 terawatts of temporally clean pulses (ASE contrast exceeding 10^-13 Wcm^-2) were focused to a 1.2 micron spot size with intensities exceeding 10^21 Wcm^-2. The energy spectra observed show distributions from protons accelerated from the front and rear surfaces. A weak short pulse prepulse is introduced before the main pulse and removes the contribution from the frontside, with the acceleration on the rear intact. This allows for the observation of narrow energy spreads. Targets used ranged from 50 nm to 200 nm SiN and 1 um to 13 um Mylar. The various thicknesses resulted in trends of maximum energy and energy spread versus thickness. The phenomena occurring for targets of such thickness rules out the mono-energetic suggests that the mechanism for acceleration is Target Normal Sheath Acceleration. Particle-in-cell simulations of the interaction were performed at high resolutions at conditions matching the experiment, providing further insight into the interaction.

8079A-14, Session 4

Coherent transition radiation generated by a femtosecond electron beam from an optically injected laser-plasma accelerator

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Laser-plasma accelerators, driven by ultraintense and ultrashort laser pulses, sustain accelerating gradients of several hundred giga-volts-per-metre and can deliver high quality electron beams with low energy spread, low emittance and up to giga-electron-volt peak energy. The use of two colliding pulses in a collinear geometry can produce a stable source of electrons that is easily tunable in energy. Here, we report on results of recent experiments with two laser beams colliding with an angle of 135°, thus having the advantage of protecting the laser system from any feedback and facilitating immediate access to the electron beam.

For temporal characterization of the electron beam, we measure coherent optical transition radiation in a wide spectral band. Measurements of the absolute number of photons in the mid-infrared spectral band indicate that the electron bunches have durations of only a few femtoseconds. The shape and absolute intensity of the measured CTR spectrum agrees with analytical modeling of electron bunches with durations of 3 to 5 fs [full width at half maximum (fwhm)] and peak currents of 3 to 4 kA, depending on the bunch shape.

Under certain conditions, we observe strong oscillations in the visible part of the CTR spectrum. A detailed Fourier analysis reveals that these spectral modulations result from interference of radiation produced by multiple electron bunches. The bunch separation is related to the fringe separation and shifts with plasma density but is always an integer number of plasma wavelengths. It is found that electrons are injected in single- and multiple buckets up to at least ten plasma wave periods behind the first electron bunch.

8079A-15, Session 4

Towards single-shot temporal characterization of laser plasma accelerated electron bunches by coherent transition radiation

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Laser driven plasma accelerators offer the prospect of a new source of relativistic electron beams with inherently short pulse durations. One of the key parameters to be determined is the temporal profile of the electron bunch. Although recent experiments confirm the expectation of ultrashort bunches with duration below 10fs, the exact longitudinal bunch profile is still to be determined. We report on progress towards measuring the temporal profile of electron bunches produced by laser-wakefield acceleration, based on the detection of coherent transition radiation emitted at a metal-vacuum boundary and spanning a region from optical to THz frequencies. To access the the low energy part of the spectrum, a spectrometer based on pyroelectric detectors was developed extending the range to frequencies in the THz regime, and allowing single-shot operation.

First measurements of shape and intensity of the acquired spectra agree with analytic modeling of electron bunches with a duration <10fs (assuming a Gaussian beam profile). The design of the spectrometer and recent experimental results will be presented and discussed.

8079A-16, Session 4

Observation of long range coherent OTR from LPA electron beams

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We report the observation of coherent optical transition radiation (COTR) from electron bunches that have propagated for up to 4 m from the exit the laser plasma accelerator (LPA) inside a vacuum tube.

Transition radiation images and their spectra, produced by electrons passing through two separate foils (located from the LPA at 2.3 m and 3.8 m) were recorded with a high resolution imaging system and spectrometer, respectively. Transition radiation in the visible wavelength regime was measured that had signal levels that are more than two orders of magnitude greater than expected from incoherent emission, indicating that femtosecond structure on the electron beams persists over multi-meter scale propagation distances. The persistence of femtosecond timescale structure on the bunches after multi-meter propagation, implies an upper limit for energy spread and emittance. Different coherent enhancement between the two stations has also been observed, consistent with dynamic changes of the bunch structure due to beam velocity bunching. Work supported by US DOE Contract No. DE-AC02-05CH11231.

8079A-17, Session 4

Electro-optic detection of ultrashort electron beams: moving beyond the transverse optical phonon resonance

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Recent theoretical work has provided new insight into the physics involved in Electro-Optic detection of ultrashort relativistic electron beams. Typically, Electro-Optic detection has been restricted to bunches as short as ~100 fs. This limitation is due the transverse optical (TO) phonon resonance that most Electro-Optic materials exhibit in the THz range. Once the electron bunch profile becomes short enough so that a significant portion of its frequency components reside above this resonance frequency, the temporal profile of the space charge field begins to distort as it propagates through the crystal. This distortion becomes more significant as the bunch becomes shorter and destroys the ability of current decoding techniques to resolve the original bunch profile.

It is possible to circumvent this issue by realizing that for these higher frequency components it is no longer valid to rely on the formalism of Pockels effect. Instead, sum and difference frequency generation must be taken into account. A theoretical formalism has been developed that fully incorporates nonlinear three-wave mixing to model this process. From this formalism, a new technique that provides the order of magnitude increase in resolution necessary to measure the ultrashort bunches produced by laser wakefield accelerators has been developed. This technique, bandwidth mixing cross-correlation frequency resolved optical gating (BMX-FROG), provides both frequency and phase information about the generated pulse from which, in principle, the temporal profile can be reconstructed.

The BMX-FROG has been modeled numerically and the results of which show the nonlinear mixing expected for sub-100 fs bunches. These results show excellent agreement when compared to those generated using the nonlinear optics modules recently incorporated into the turboWAVE code.

Experimental benchmarking of this technique is currently underway at the US Naval Research Laboratory. This is done using an ultrashort THz pulse as a surrogate for the ultrashort electron beam produced by a laser wakefield accelerator. Instead of the standard THz surrogate generated by means of optical rectification in a nonlinear crystal, the THz pulse is being generated using two-color mixing within plasma. This type of THz pulse generation method is advantageous since it is capable of producing frequency components in the 10's of THz range. Current results from theory, simulation, and experiment will be presented.

8079A-18, Session 5

Radiation signatures of laser-driven wakes

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In laser driven accelerators, an ultra-intense laser pulse often propagates in an underdense plasma to produce some form of wake. The interaction of the laser radiation with the plasma leads to a variety of scattering mechanisms, which can be used to understand the wake structure and its effect on electron trapping. For example, in the case of a resonantly driven quasi-linear wake, spectral broadening due to photon acceleration and deceleration replaces the discrete Stokes and anti-Stokes peaks that appear in the long pulse regime. On the other hand, in the self-guided regime, a weak bubble is formed, which emits electro-optic shocks at the second harmonic of the drive laser. The form of this second harmonic radiation can be correlated with electron trapping. At the same time, red and blue shifted radiation is produced which can have some of the features of both the long and short pulse regimes. We have developed a numerical framework called turboWAVE which supports several models pertinent to accelerator modeling. The framework is designed so that models built on it are able to solve problems on an arbitrary structured grid with any dimensionality up to three. The particle-in-cell models are particularly useful for modeling highly nonlinear ultra-short pulse laser-plasma interactions. Various photo-ionization models are supported, as well as a ponderomotive guiding center option. In the quasi-linear case, the ponderomotive guiding center algorithm is advantageous since it allows for averaging over optical cycles, and can be implemented in axisymmetric geometry. It is predicted that the main radiative signature of wakefield generation in the quasi-linear regime is photon deceleration. However, this can be cleanly observed only in very long preformed plasma channels, and experimental confirmation has been difficult. In the self-guided regime, fully explicit particle-in-cell simulations are needed to properly model the wide range of scattered frequencies that are produced. Relating the near-field data produced by the simulations to the far-field data collected in experiments is sometimes nontrivial. Three dimensional wavenumber spectra at sequential time levels can be used to estimate the far field distribution. It is found both experimentally and numerically that two primary features are produced: conical emission at the second harmonic of the drive laser (electro-optic shock), and broad red and blue shifted satellites. At densities just high enough for self-guiding, the second harmonic radiation takes the form of two symmetric ring arcs peaking in the polarization direction. Based on theoretical considerations, it is expected that the narrower the angular distribution of the ring, the longer the self-guided propagation distance. It is also expected that the red shifted satellite should be stronger than the blue, but this is not typically observed in experiments. The simulation results suggest this may be related to the angular characteristics of the emission, as well as the spectral response of silicon detectors. As the plasma density is raised, the second harmonic emission breaks up into multiple rings and self-trapped electrons appear. In some cases the wake structure is violently disrupted due to hosing, with adverse effects on the electron spectrum.

8079A-19, Session 5

Laser-powered dielectric-structures for the production of high-brightness electron and x-ray beams

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Laser powered accelerators have been under intensive study for the past decade due to their promise of high gradients and leveraging of rapid technological progress in photonics. Of the various acceleration schemes under examination, those based on dielectric structures may enable the production of relativistic electron beams in breadbox sized systems. When combined with undulators having optical-wavelength periods, these systems could produce high brilliance x-rays which find application in, for instance, medical and industrial imaging. These beams also may open the way for table-top atto-second sciences. Development and testing of these dielectric structures faces a number of challenges including complex beam dynamics, new demands on lasers and optical coupling, beam injection schemes, and fabrication. We describe one approach being pursued at UCLA-the Micro Accelerator Platform (MAP). A structure similar to the MAP has also been designed which produces periodic deflections and acts as an undulator for radiation production, and the prospects for this device will be considered.

The MAP avoids many of the problems associated with optical-scale structures by using transverse laser coupling, a slab-symmetric geometry, flat ribbon-like electron beams and a resonant accelerating mode. These features avoid the need for complex optical coupling schemes, reduce wakefield and space-charge associated beam disruptions, and make efficient use of the laser power. Integrated electron sources have also been designed which avoid many of the problems associated with external injection.

Complete, monolithic structures are being now fabricated using lithography, thin film deposition and other nanotechnology. The lessons learned from the multi-year effort to realize these devices will be presented. The testing of these structures is demanding and will be detailed, including laser damage and breakdown measurements. Challenges remain with acceleration of sub-relativistic beams, focusing, beam phase stability and extension of these devices to higher beam energies. Our progress in addressing these hurdles will be summarized.

Finally, the demands on laser technology and optical coupling will be detailed. A recent call by DARPA places extreme demands on peak and average powers of the lasers to be used in driving these accelerating structures. We will summarize our approach and future needs for suitable solid-state lasers.

8079A-20, Session 5

A kinetic treatment of radiation reaction effects

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In the large accelerating fields generated in the most advanced particle accelerators and light sources currently available, electron bunches undergoing quasiperiodic oscillations can emit a significant fraction of their energy in electromagnetic radiation over a single cycle. As we proceed to higher energies and greater accelerating gradients, we are approaching the regime where the back-reaction on the electrons of their own radiation fields can no longer be ignored as negligible in comparison to the applied forces.

The problem of reliably accounting for radiation reaction is beset with difficulties. The Lorentz-Dirac equation which describes the motion of a radiating charged particle exhibits unphysical behaviour, such as exponentially increasing acceleration and non-causal responses. We seek to circumvent these pathologies by embedding the Lorentz-Dirac equation in a kinetic description of the electron bunch, describing a particle distribution function on a generalized phase space involving acceleration variables in addition to position and momentum. By working only with low order moments of the particle distribution, the question of eliminating the non-physical solutions may be incorporated into the search for an appropriate equation of state.

A suitable equation of state may be obtained by generalizing the notion of the warm plasma closure of Vlasov dynamics in the absence of radiation reaction, in which the momentum spread is assumed small. Using such a closure scheme, we apply the resulting fluid model to explore in detail how radiation reaction affects the evolution of an electron bunch undergoing betatron oscillations in a laser wakefield accelerator.

8079A-21, Session 5

Coherently enhanced radiation reaction effects in laser-vacuum acceleration of electron bunches

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The recent availability of ultra-intense laser pulses has led to increased efforts to develop novel compact acceleration schemes for electron beams. Of these, laser-vacuum acceleration schemes are attractive because of their simplicity in that they avoid the use of a plasma medium by directly irradiating electron bunches in vacuum by a high-intensity laser. Often, however, these schemes are problematic because the accelerating mechanism is the ponderomotive force, which tends to expell the electron bunch out of the laser beam before appreciable acceleration has occured (ponderomotive instability).

We consider the possibility to exploit coherently enhanced radiation reaction as a stabilizing effect in laser-vacuum acceleration schemes. When irradiated by a laser pulse, the bunch electrons scatter a fraction of the light due to their oscillatory quiver motion in the optical field of the pulse, which is known as Thomson scattering. The accompanying recoil from the scattered light is the classical radiation reaction, which usually affects the motion of the electrons negligibly. However, when the bunch is smaller than the laser wavelength, the bunch electrons scatter light coherently, yielding a strongly enhanced radiation reaction force.

Radiation reaction is described by the so-called Lorentz-Abraham-Dirac equation of motion. By analyzing this equation using the multiple-scale expansion technique, we show analytically that radiation reaction acts as a radiation pressure in the laser beam direction, and as a viscous force in the radial direction. Thus coherently enhanced radiation reaction both increases bunch acceleration along the laser beam and opposes the problematic ponderomotive instability, which shows its potential for laser-vacuum bunch acceleration. However, due to Coulomb expansion of the electron bunch, coherent radiation reaction takes effect only in the initial stage of the laser-bunch interaction while the bunch is smaller than the wavelength. Still, it is shown that this initial stage can have observable effects on the trajectory of the bunch. Moreover, by scaling the system to larger bunch charges, the radiation reaction effects are further increased. By numerical integration of the Landau-Lifshitz (LL) equation of motion (which is equivalent to the LAD equation), this increase is shown to be such that radiation reaction may even suppress the radial instability normally found in ponderomotive acceleration schemes.

Yet, the applicability of the LL equation still needs to be validated experimentally. But since scattering electron bunches coherently amplify the classical radiation reaction effect, this is precisely what becomes possible using the presented experimental scheme.
Thus subwavelength electron bunches are also interesting as an experimentally accessible model of classical point charges.

See also: P.W. Smorenburg et al., Laser and Particle Beams 28, 553-562 (2010).

8079A-22, Session 6

Ion acceleration with prospective sub-PW CO2 lasers

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In relativistic laser-matter interactions, the maximum laser energy transferred to a charged particle is determined by the ponderomotive coupling efficiency scaling linear to the laser intensity and quadratic to its wavelength (~Iλ^2). This relationship implies that we will gain certain benefits from running experiments with long-wavelength laser sources, such as generating high-energy particles at low laser intensity, or increasing the process yield at the same peak power.

Accordingly, searching for practical solutions for producing high-power, ultra-short pulses of long-wavelength radiation is one of the essential tasks in extreme-light science. The ability to deliver high-power radiation in the mid-IR (~10 µm) spectral region secures a niche for CO2 lasers in the laser science unfilled by otherwise more powerful solid-state lasers.

Possibly the strongest motivation for developing ultra-fast CO2 laser technology comes from ongoing experiments on ion acceleration. Thus, recently the UK-US international collaboration at BNL's user facility demonstrated that an ionization shock driven into a gas target by the pulse from a CO2 laser generates MeV proton beams with an extremely narrow energy spread (~4%), and much higher peak-spectral-brightness (almost 10^9 per MeV per sr) than do other methods.

There is a two-fold benefit from using a longer wavelength. First, the scaling of the hadron's energy with λ^2 , and second, the 1/λ^2 scaling of the critical plasma density means that the CO2 laser can generate a plasma-acceleration medium in low-density gas targets, 10^19 cm-3. A gas jet readily affords such density, thereby supporting process improvements, such as facilitating high repetition-rate operation, and allowing easy adjustments of the target's density and material. Therefore, combining an ultra-intense CO2 laser with a gas-jet target might offer us a unique opportunity for a breakthrough in the field.

To fully realize all these capacities offered by wavelength scaling, CO2 lasers must operate deep within relativistic regime defined by the condition a_0>>1 , where a_0 is the normalized vector-potential. The condition of a_0=1 is reached at the CO2- laser intensity 10^16 W/cm2 that, assuming it is close to the diffraction's limiting focus, requires Terawatt (10^12 W) peak power. Therefore, achieving a_0>10 necessitates having lasers of 100-TW or sub-PW class. Theoretical estimates show that such CO2 lasers should attain ~100 MeV proton energies via radiation-pressure acceleration.

Developing the new generation of ultra-fast IR lasers entails identifying new regimes for operating molecular-gas lasers. We outline the technical problems and their possible solutions in this talk. We discuss our strategy for upgrading the CO_2 laser that includes optimizing the generation of 10-μm ultra-short pulses, assuring higher amplification in the CO_2 gas under combined isotopic- and power-broadening effects, and shortening the post-amplification pulse to a few laser cycles (150-200 fs) via chirping and compression.

8079A-23, Session 6

Conversion efficiency and angular distribution measurements of ion acceleration in the break-out afterburner regime

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In the past 10 years laser acceleration of protons and ions was predominantly achieved laser light interacting with micrometer scaled solid matter targets in the TNSA regime, yielding conversion efficiencies of around 1% for all but the largest laser systems and characteristic beam distributions around the target normal. Ion acceleration based on this acceleration mechanism seems to have saturated in terms of conversion efficiency and particle energy, remaining too low for most advanced applications.

The ultrahigh contrast and relativistic intensities (>10^20 W/cm^2) available at the LANL Trident laser open up sub-micron solid matter laser interaction dominated by relativistic transparency of the target, enhancing conversion efficiencies and strongly influencing ion angular distribution, which is oriented along the laser axis rather than the target normal. Ion acceleration within this Break-Out-Afterburner (BOA) regime has already shown carbon ion energies of more than 0.5 GeV. Herein we present a detailed experimental study of this acceleration regime and comparison with TNSA results in terms of conversion efficiency from laser energy into proton and carbon ion energy and angular ion distributions. The use of a novel wide angle ion spectrometer (iWASP) allows for high resolution measurements of the angular ion distribution and significantly increases accuracy of conversion efficiency measurements. Measured efficiency within the BOA regime for carbon ions is approaching 10% and significantly increasing laser to ion energy conversion efficiency over the TNSA regime. Thus the BOA regime brings laser ion acceleration into parameters relevant to a wide array of applications, ranging from fusion energy production to medicine and tumor therapy.

8079A-24, Session 6

Fast ions generation from nanostructure target irradiated by high intensity short laser pulse

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One of the problems of laser particle acceleration physics is increasing of transformation of laser pulse energy into particle energy. Rather recently it was revealed that transformation of laser energy in ion energy increases at use a thin foils limited in size anywhere laser radiation absorption of such targets was not so high.

In the present report it is offered to increase target absorption up to 95% and to optimize parameters of a relief and basic part of a target so that the additional absorbed energy is transferred mainly to the accelerated protons. The choice of optimum characteristics of a target is made by means of analytical and numerical modeling of a target set with characteristics near to optimum values. We investigated plastic foils consisting of a substrate in the form of a few hundereds nanometers with different elements of a relief put on this substrate. The laser pulse irradiated targets had relativistic intensity and femtosecond duration.

It was found that the optimal relief is capable to increase absorption of a target to extremely high values. The shape of profile does not change significantly the absorption. For effective acceleration of ions the volume of relief should be less than the volume of the basic foil, otherwise absorption can be high but efficiency of ion acceleration low. The additional absorbed energy passes in energy of heavy ion components more effectively. To redirect energy to protons it is necessary to use a heterogeneous target. Laser pre-pulse is capable to destroy a relief and to change these results. With the account of laser pulse contrast larger relief and thicker foil can be the optimum.

8079A-25, Session 6

Key conditions for stable ion radiation pressure acceleration by circularly polarized laser pulses at moderate intensities

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Recent exciting results have made it very clear that radiation pressure acceleration (RPA) may have great potential to revolutionize laser-driven ion acceleration. However, the instability issue of ion acceleration has been appeared to be a fundamental limitation of the RPA scheme. Solving this issue is very important to the experimental realization and exploitation of the scheme.

So far, stable acceleration regimes can be found at ultrahigh intensities > 1022W/cm2, when the plasma slab becomes relativistic rapidly suppressing the growth of instabilities and for the cases where the acceleration profile is transversely uniform leading to reduced heating and decompression of electrons (by tailoring density or intensity distributions). However, for RPA using moderate (currently achievable) lasers, modifications of transverse profiles are insufficient to preserve stable RPA. To our understanding, the key criterion for stable ion acceleration has still not been clarified, in particular that for the case of moderate laser intensities.

In our recent work, we have identified the key condition for efficient and stable ion RPA from thin foils by CP laser pulses at moderate intensities. That is, the ion beam should remain accompanied with enough co-moving electrons to preserve a local "bunching" electrostatic field during acceleration. In realistic LS RPA, the decompression of the co-moving electron layer leads to a change of local electrostatic field from a "bunching" to a "debunching" profile, resulting in premature termination of acceleration. One possible scheme to achieve stable RPA is using a multi-species foil. Two-dimensional PIC simulations show that 100 MeV/u monoenergetic C6+ beam are produced by irradiation of a Cu-C-mixed foil with CP lasers at intensities 5 ×1020W/cm2 achievable by current day lasers.

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8079A-26, Session 6

Relativistic electron dynamics in laser-nanofoil interactions: towards ultra-dense electron mirrors

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While high quality electron beams are routinely generated in under-dense plasmas and have already proven usability in first applications, solid density targets studied so far seem unattractive in this respect.

Here, strong coulomb fields immediately set up during the laser target interaction counteract the ponderomotive force of the laser and thus suppress significant energy gain of electrons in the laser field. However, this scenario drastically changes when the areal density of the target is significantly reduced which can be achieved with a target of only a few nm thickness.

We present experimental evidence of efficient electron extraction when irradiating a few nm thin foil with a high-power laser. The data taken at two experiments with inherently different laser systems gives for the very first time an intriguing insight into the mechanism of electron bunch production by the radiation pressure of a powerful laser. The observed signatures are in good agreement with recent theoretical predictions on electron sheet generation from ultra-thin foils [1, 2, 3]. Our results represent a major step towards the generation of a dense, relativistic electron mirror that promises the efficient X-ray production via Thomson backscattering.

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8079A-27, Session 7

Monodimensional Airy beam generation using an amplitude mask and lens aberrations

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We report a simple way for generating monodimensional Airy beams employing only passive optical elements. That kind of beams exhibit unusual features as the ability to remain diffraction-free over long distances while they intensity maximum shows a curve trajectory during propagation, so it was applied to microparticle manipulation. The Airy beams can be generated through the Fourier transform of a Gaussian beam with a cubic phase modulation, which usually implies the employment of liquid crystal display as phase mask. We show that under certain operational conditions, the Airy beams can be obtained using the coma aberration of a lens and an amplitude mask which limits the effect of oder aberrations. Such system has the advantage that since it is formed only with passive optical elements is more stable.

8079A-28, Session 7

Laser pulse shaping due to self-induced relativistic transparency in laser-nanofoil interactions

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Shapes of the laser pulses transmitted through thin nanofoils due to self-induced relativistic transparency in intense, high contrast laser (80J, ~600 fs, >1020 W/cm2 and 10-10 contrast) - nanofoil interactions were measured using a single shot second harmonic frequency resolved optical gating (FROG) system [Palaniyappan, et al., RSI, 81, 1 (2010)]. The FROG measurements show asymmetric pulse shapes, pulse shortening up to a factor of 2 and faster rise times on the leading edge than the falling edge. Part of the incident pulse is reflected/absorbed by the over dense plasma until it becomes relativistically under dense and transparent to the rest of the pulse. The measurements are qualitatively in agreement with a 1-D PIC simulation. Transmitted laser pulse shapes through 3 nm thick foil show large variations due to early target expansion.

8079A-29, Session 7

Energetic proton beams from plastic targets irradiated by an ultra-intense laser pulse

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Characteristics of proton beams from plastic foils have been found to be different those from metal foils in number and energy.

Based on the experimental observation, ARIE (Acceleration by a Resistively Induced Electric field) has been proposed, which predicts the proton beams originates from the front side.

Experimental observations obtained from an aluminum-coated plastic target support the front side acceleration.

An energy enhancement by a factor of 1.4 was also observed with the coated target when the coated-aluminum layer was positioned in the rear side, which could be explained with the ARIE model

By considering target structure, an idea to effectively enhance the contrast ratio of the laser pre-pulse will also be presented with numerical simulation.

8079A-30, Session 7

Simulations of short pulses laser interaction with targets having a submicron surface structure: energy absorption and ion acceleration

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Interaction of ultra-short intense laser pulse with target results in heating and acceleration of electrons. Their subsequent expansion from the target surface is accompanied by Target Normal Sheath Acceleration (TNSA) of ions. Energetic ions accelerated from thin foils by short intense laser pulses are interesting for various applications, e.g. radiography, isotope production, isochoric heating. However, it is desirable to increase the efficiency of the ion acceleration process and the maximum ion energy.

The maximum ion energy can been increased by decreasing the foil thickness and using a high contrast laser pulse. However, energy absorption of short prepulse-free intense laser pulse on the flat foil surface may be relatively low especially at normal incidence. The laser energy absorption may be boosted by the presence of microscopic structures on the laser irradiated surface. In consequence, a target with reduced thickness and a sub-micron structure on the surface may benefit from both higher absorption and more efficient hot electron energy coupling into fast ions, when irradiated by short high contrast laser pulses.

Using 2D PIC simulations it is demonstrated that a suitable candidate for such target may be a thin foil covered by a monolayer of polystyrene spheres with the diameter of the order of the laser wavelength. The conversion efficiency and maximum energy of fast protons accelerated from this target are calculated for both normal (or near normal) and oblique incidence of the p-polarized laser pulse and compared with the results calculated for flat foil. The dependence of laser energy absorption on the size of polystyrene microspheres, the inhomogeneity of the monolayer, or a finite plasma density profile (corresponding to nonnegligbile laser prepulse) on the target surface are studied as well.

8079A-31, Session 7

RF photogun for external injection of electrons in a laser wakefield accelerator

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We have developed a 2.5 cell, 3 GHz RF accelerator specifically to inject electrons in a laser wakefield accelerator (LWA). The electron bunches are accelerated to around 3.5 MeV and focused at 1.3 m from the accelerator using a pulsed solenoid. The critical parameters for bunches injected into a laser wakefield accelerator are the bunch charge that can be focused into the plasma (channel), its energy, timing and pointing stabilities.

Bunches between 0 and 50 pC were focused onto a phosphor screen at the position of the entrance of a plasma channel. The (RMS) bunch size was 30 µm at 0.1 pC and increases to 70 µm at 50 pC. The energy of the bunches at the chosen settings was measured to be 3.71 MeV with 0.01 MeV energy spread (at 10 pC). The 3 GHz oscillator is synchronized with the Ti:Sapphire laser system which is used for photoemission (and will later also be used to drive the laser wakefield). The synchronization between the two systems is better than 20 fs. The measured energy fluctuations were less than 2 keV, which is consistent with the stability of the output power of the modulator of 0.05% and a negligible contribution due to timing jitter between the laser and the accelerator. The jitter in arrival time between the accelerated electron bunches and the laser caused by these fluctuations is less than 50 fs. Finally, the pointing stability of the focused electron bunches was determined from 100 consecutive shots at 1 Hz to be 6 µm (RMS).

GPT (General Particle Tracer) simulations have been performed using the measured bunches as input for LWA. The simulations show that up to 5 pC of charge can be accelerated to energies of around 500 MeV using realistic plasma and laser parameters. The measured bunch parameters in combination with the simulations show how external injection of pre-accelerated electrons can be a viable alternative to other injection mechanisms.

8079A-32, Session 8

Numerical modeling of plasma-based accelerators in ultra-relativistic boosted frames

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In laser wakefield acceleration (LWFA) a short laser pulse with duration lower than 100 fs, and with intensity above 10^18 W/cm^2, excites large amplitude plasma waves with accelerating gradients in excess of 1 GeV/m. As state-of-the-art experiments demonstrated electron acceleration beyond the GeV energy barrier in cm scale plasmas [1], future laser systems about to come online, such as those of the ELI or HiPER projects, will enable multi 10 GeV electron bunch acceleration in meter scale plasmas [2].

Numerical simulations play a key role in the design of future LWFA experiments. The use of standard full particle-in-cell algorithms, however, is unpractical for single stage 1-1000 GeV LWFA modeling since more than 10^6 CPU hours are required to simulate the corresponding propagation distances of 0.1-100 meters. Recently, drastic reductions of the computational requirements of LWFA numerical simulations was achieved by employing relativistically boosted frames [3]. While this novel approach performs no physical approximations, it also allows for computational speed ups of several orders of magnitude in comparison to standard full PIC codes.

This work presents LWFA OSIRIS simulations in relativistic boosted frames using gamma factors above 100. The laser pulse is initialized at its focal plane, thus permitting the reduction of the transverse dimensions of the simulation box, further enhancing the computational gains. Simulations performed in weakly relativistic regimes showed very good agreement with scalings for the maximum energy gain in LWFAs. Significant computational speed ups were achieved.

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8079A-33, Session 8

Physics considerations for laser-plasma linear colliders

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Physics considerations for a next-generation linear collider based on laser-plasma accelerators are discussed. The ultrahigh accelerating gradient of a laser-plasma accelerator and short laser coupling distance between accelerator stages allows for a compact linac. Two regimes of laser-plasma acceleration are discussed. The highly nonlinear regime has the advantages of higher accelerating fields and uniform focusing forces, whereas the quasilinear regime has the advantage of symmetric accelerating properties for electrons and positrons. Scaling of various accelerator and collider parameters with respect to plasma density and laser wavelength are derived.

Reduction of beamstrahlung effects implies the use of ultrashort bunches of moderate charge. The total linac length scales inversely with the square root of the plasma density, whereas the total power scales proportional to the square root of the density. A 1 TeV center-of-mass collider based on stages using a plasma density of 10^17/cm^3 requires tens of J of laser energy per stage (using 1 micron wavelength lasers) with tens of kHz repetition rate. Coulomb scattering and synchrotron radiation are examined and found not to significantly degrade beam quality. A photon collider based on laser-plasma accelerated beams is also considered. The requirements for the scattering laser energy are comparable to those of a single laser-plasma accelerator stage. Work supported by US DOE Contract No. DE-AC02-05CH11231.

8079A-34, Session 8

Polarization-dependent ponderomotive force in a standing wave

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In a certain sense, the electromagnetic (EM) standing wave may be considered the prototype field configuration in which ponderomotive (gradient) forces play a dominant role, since in between the nodes and antinodes of the wave the field changes from zero to maximum, leading to large field gradients. A standing wave produced by two counterpropagating EM waves with a wavelength of 800 nm and a very modest, nonrelativistic peak field intensity of 1015 W/cm2, for example, already causes ponderomotive forces equivalent to accelerating fields of the order of 1 GV/m. Nevertheless, up to now most analytical work concentrated on the ponderomotive force in a running EM wave rather than a standing wave, leading to the well-known Gapanov-Miller ponderomotive force [1] proportional to the field gradient and always directed towards low field regions. However, in 2005 Kaplan and Pokrovsky [2] derived time-averaged equations of motion for an electron in several examples of standing waves, showing that in some configurations the ponderomotive force can change direction and point to high field regions, contrary to the Gapanov-Miller force.

We derive the ponderomotive force formula for the general standing wave of nonrelativistic intensity, using an order expansion method. We thereby generalize the results of Kaplan and Pokrovsky, which follow directly from our formula. It is shown that the ponderomotive force is still of gradient form, but contains polarization-dependent terms in addition to the Gapanov-Miller force. Depending on the configuration, the ponderomotive force can point to low field regions, to high field regions and it can even vanish completely despite the large field gradients in the standing wave. Our theory predicts the ponderomotive force in all three spatial directions, and it admits realistic, non-ideal standing wave fields that are not fully plane and also have gradients parallel to the nodal planes.

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8079A-35, Session 8

Nonlinear phase velocity of intense laser-driven plasma waves

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The phase velocity of plasma waves are of fundamental importance to many areas of plasma physics. In laser-plasma accelerators, the dynamics of the accelerated electrons is strongly affected by the plasma wave phase velocity. The phase velocity determines the dephasing length (distance for a relativistic particle to outrun the plasma wave and move out of an accelerating phase) and, hence, the maximum energy gain of the electrons in the plasma wave, as well as the trapping threshold for background plasma electrons and the maximum amplitude of the plasma wave. The plasma wave phase velocity driven by a short pulse laser is intrinsically related to the laser velocity and evolution of the drive laser. In this talk we discuss the effects of laser evolution and propagation on plasma wave excitation by a relativistically intense, short-pulse laser propagating in underdense plasma. We show that in the high-intensity, nonlinear regime, the nonlinear laser velocity is significantly greater than the nonlinear plasma wave phase velocity. For a matched laser, the phase velocity of the excited plasma wave decreases as the pulse propagates owing to laser evolution (frequency red-shifting and pulse steepening). This reduces the energy gain and efficiency of laser-plasma accelerators that use a uniform plasma profile. For the case of a strongly focused laser pulse, we show the effects of a converging and diverging laser on the excited plasma wave phase velocity, and present a method to locally trigger electron injection via phase velocity control.

8079A-36, Session 9

Generation of energetic protons from GeV to TeV

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The theoretical research works on proton and ion acceleration done by our group are reviewed. A complex target consisting of a front horizontal slice adjoining a conventional heavy ion and proton double-layer slab are used to produce more-fast moving hot electrons to enhance the target-normal sheath acceleration (TNSA) so that the protons in the proton layer can be accelerated to energies more than three times, and the energy spread halved, that from the simple double-layer slab [1]. A sandwich target design with a thin compound ion layer between two light-ion layers and a micro-structured target design are proposed for obtaining efficiently monoenergetic heavy-ion beams [2]. Radiation pressure acceleration from multi stage shock acceleration to continuous light sail acceleration for ultra thin foils is used to generate GeV protons [3, 4]. Longitudinal and transversal instabilities are studied theoretically and with three dimensional particle-in-cell simulations. The foil thickness for light pressure acceleration is studied. Quasi-single-cycle relativistic laser pulse is generated with an accelerated flying foil [5]. In order to accelerate protons to higher energy up to TeV, wake acceleration is proposed. Mixed plasma is used to enhance the wake and radiation pressure acceleration is used to help protons to be easily trapped in the wake.

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8079A-37, Session 9

PIC simulations of ion acceleration in laser irradiated submicron droplets

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Advent of chirped pulse amplification enabled generation of very short laser pulses (10's - 100's fs) of a high intensity (I > 10(18) W/cm(2)). The acceleration of ions to very high energies belongs to the most important applications of short-pulse laser-target interactions. The physical mechanism of ion acceleration in clusters of submicron sizes differs from that in widely used foil targets. In small clusters of diameter of several nm, all electrons are extracted from the cluster under the action of laser field making the cluster positively charged. In this regime of Coulomb explosion, electrons do not affect the dynamics of ion acceleration as the ions are accelerated in the electrostatic field of their own charge. In larger clusters of solid density, such as those in spray targets consisting of water droplets of sizes above 100 nm [1], only a part of electrons can be extracted from ionized microdroplet and ion acceleration is driven both by thermal expansion and by Coulomb-like explosion. The relative significance of the individual mechanisms depends on the cluster (droplet) size and on the laser intensity [2].

In our recent study [3], we have investigated field ionization of submicron water droplets employed in experiment in Ref. [1]. We found by using 2D PIC simulations that (contrary to previous predictions) oxygen atoms are ionized up to Z>=6 in the whole submicron droplet by 40 fs laser pulses of amplitude a0>=0.5. In this contribution, our previous work is briefly summarized and further extended by considering various droplet sizes, density profiles, laser intensities and pulse duration. We compare energy distribution functions of accelerated protons and oxygen ions and identify parameters favorable for efficient proton acceleration.

It is shown that irradiated submicron droplet expands rapidly already during the laser pulse duration and electrons are gradually expelled from the target. For higher laser intensity or/and longer laser pulse, the expanding droplet plasma starts to be underdense at the end of interaction, which limits the absorption of the laser pulse energy into the plasma, thus, the efficiency of ion acceleration. With increasing laser intensity, the initial target density profile is less imporant, however, a relatively large overdense cluster core at the beginning of the interaction is essential for higher proton acceleration efficiency.

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8079A-38, Session 9

A new mechanism for hot electron generation increasing the proton energy in laser-ion acceleration

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We present a comprehensive numerical and analytic study of the

interaction of an ultra-intense laser pulse with micro-structured conical solid targets with a flat top. Using such targets, a new record in maximum energy of laser-accelerated protons has been established in 2009 at the TRIDENT 200 TW high-contrast, 80 J laser beam of the Los Alamos National Laboratory (USA). The main experimental results from Cu Kα 2D imaging, RCF film stacks and spectrometers suggest that the high proton energies observed are largely independent from the details of the cone geometries and especially from the neck diameter -as long as the laser-wall interaction was dominant. In the view of these results we argue that microfocusing of the laser light inside the cone throat [1] is not be the dominant mechanism explaining the proton energy gain.

In order to elucidate the plasma processes leading to the record breaking proton energies, we performed a numerical study with 2D PIC-simulations. When the laser interacts with the cone walls - that is in thin cone necks (less than the laser waist) or when the laser grazes along a wall - we find an increase in hot electron temperature beyond the usual ponderomotive energy. Moreover, the hot electron temperature is not correlated to the microfocused intensity in our simulations. Rather, based on our 2D PIC simulations, we propose that the increase in proton energy observed from flat-top cones compared to regular flat foils is due to a new, scalable acceleration mechanism of electrons. Electrons, confined at the cone wall surface by self-created magnetic and electric fields, can be directly accelerated by the laser light pressure. The electrons can hereby gain energy significantly higher than the ponderomotive energy. With the help of a detailed analysis of individual electron trajectories and field interaction we elucidate the acceleration mechanism and draw conclusions for its scalability and for future optimized target design.

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8079A-39, Session 9

Three-dimensional multi-scale modeling of ion acceleration in laser-plasma interactions

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Ion acceleration from the interaction of ultrahigh intensity lasers with solid-density targets is a promising approach for compact and bright ion sources, of interest to several applications such as tumor therapy, radiography, or ion fast ignition. Numerical simulations play an important role in understanding the underlying physics and optimizing the ion beam energy and quality of these experiments. However, the different spatial and temporal scales involved make this modeling extremely demanding and multi-dimensional full-scale simulations are not yet possible to accomplish. The understanding of the importance of multi-dimensional effects and the self-consistent coupling of the different scales has been a long-standing problem.

Recently, Cohen et al. [J. Comp. Phys. 229, 4591 (2010)] have proposed a novel framework for modeling inhomogeneous plasmas that merges accurate collisional PIC models between regions where only the field solver is reduced in the collisional region. This framework has been integrated into OSIRIS 2.0 [R. A. Fonseca et al, LNCS 2329, III-324 (Springer-Verlag, 2002)], which together with higher order particle shapes and dynamic load balancing is allowing the first multi-dimensional simulations of ion acceleration in solid targets over full density and time scales.

We will demonstrate how OSIRIS can be used to perform for the first time three-dimensional full-scale simulations of ion acceleration, where the critical issues of laser absorption, electron transport in the collisional plasma, and ion acceleration will be addressed in a fully self-consistent manner. Our results, for different laser intensities, target thicknesses and compositions, shed light on the importance of multi-dimensional effects in the different ion acceleration mechanisms, and provide an integrated physical picture of the overall interaction and clear directions for future experiments.

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8079B-40, Session 10

Developing an integrated, laser-driven ion accelerator system for ion beam radiotherapy: progress and challenges

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The primary goal of the Photo-Medical Research Center (PMRC) of the Japan Atomic Energy Agency is developing an integrated, laser-driven ion accelerator system (ILDIAS) prototype for application to laser-driven ion beam radiotherapy (L-IBRT). PMRC pursues all-optical acceleration of protons to high kinetic energy (~ 250 MeV) via intense laser-plasma interaction at the target site. The ILDIAS concept is presented along with some laser and proton beam delivery requirements for radiotherapy. The ILDIAS will necessarily be comprised of several subsystems that include at least: the laser, the target, instrumentation, ion transport optics and the delivery (to the patient). Toward our higher energy goal for L-IBRT we have achieved maximum proton energies near 14 MeV in single shot experiments and also demonstrated repetition-rated (1 Hz) transport of protons with energy up to 3 MeV. At about 2 MeV 5 nanosecond bunches have been transported at a flux level 10^6 protons/cm^2 with a 5 % energy spread [1]. Also for recent cell irradiation studies we transported 20 nanosecond bunches at 2.3 MeV with flux levels of order 10^7 protons/cm^2 with a 30 % energy spread [2]. In this latter case human cancer cells received single bunch doses of 0.2 Gy. Typically we can expect the ILDIAS to produce single bunches of ~ 10 nanosecond duration with low duty factors in the range, 10^-7 to 10^-6 for 10 Hz and 100 Hz repetition-rate operation respectively. Other progress and significant challenges associated with obtaining accelerator quality proton beams using these subsystems are discussed. There is significant opportunity for use of specialized particle optics in design of beam lines; especially the first optic that must collect charge and match to downstream optics. For repetition-rated operation ILDIAS instrumentation for diagnostics and control should include transverse and longitudinal resolution of high current single bunches with prompt readout. This should be done noninvasively where possible. As examples, inline scintillator detection and correlated plasma diagnostics are being investigated as feasible candidates [3,4]. Targetry development must consider energy conversion efficiency (from laser pulse energy to relevant bunch energy) along with capability for repetition-rates of at least 10 Hz as well as metrology to verify target position and condition before each laser shot. The essential global character of ILDIAS development for L-IBRT is also emphasized in the presentation.

[1] M. Nishiuchi et al., Phys. Rev. STAB 13, 071304 (2010)

[2] A. Yogo et al., see abstract for this meeting

[3] M. Tampo et al., Physics of Plasmas 17[7], 073110 (2010)

[4] H. Sakaki et al., Applied Physics Express, in press (2010).

8079B-41, Session 10

Stable proton pulses for the measurement of the biological effectiveness of laser accelerated particle beams

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The advent of high power laser systems providing pulse rates of a few pulses per minute in the field of laser ion acceleration has brought medical applications such as ion therapy of cancer closer into reach. Although the proton energies are still not high enough for patient treatment, they are sufficient to start first experiments on dosimetry and the biological effectiveness. In contrary to conventional accelerators, the laser ion acceleration delivers proton bunches with a very high charge in short times with a broad energy spectrum. Thus new concepts in dosimetry and irradiation are necessary.

It is evident, that applications with biological material have demanding requirements to the proton energy spectrum and its stability. In this paper we present a robust scheme to provide stable energy spectra for first cell irradiation experiments performed with the Dresden 150 TW laser system DRACO at a dose rate of about 1 Gy/min. A second paper will concentrate on the radiobiological aspects of the experiment and the complex dosimetry issues.

In addition to the production of a reproducible proton spectrum the scheme involves magnetic filtering. Based on a simple non-focusing magnetic dipole equipped with two apertures it makes use of an energy dependent angular asymmetry of the proton spectra and protons with energies above 7 MeV originating from a 2 µm thick Titanium foil are led to the cell sample.

S.D. Kraft, et al., Dose dependent biological damage of tumour cells by laser-accelerated proton beams, New Journal of Physics 12, 085003 (2010)

8079B-42, Session 10

Enhanced proton beam collimation in the ultra-intense short pulse regime

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For laser-generated ion beams to be fully realised as a new compact source for high profile applications such as ion radiotherapy, fast-ignitor inertial confinement fusion or ion radiography it is important that high quality ion beam production be demonstrated. For ion beam therapy especially, there is a requirement for not only extensive control over the generated energy spectrum, but also a low emittance beam with a high degree of focusability for controlled and repeatable delivery to the patient.

An investigation to characterise laser-generated ions was carried out using the ultra-intense, short pulse (40 fs) Astra Gemini laser at the Rutherford Appleton laboratory. We have recently developed and characterised prototype fast ion diagnostics based on organic scintillators as an imaging medium. By using a selection of scintillators (each emitting at a separate wavelength) stacked together, detailed 2D spatial maps of an ion beam can be produced over a range of energies when the stack is placed in the path of the beam.

Focused laser intensities of up to 10^21 Wcm-2 were used to irradiate thin metallic foils. The proton beam divergence was seen to reduce markedly when the laser contrast (the intensity ratio between the main pulse and any preceding pre-pulse) was increased by several orders of magnitude. These results, together with 2D particle-in-cell simulations, are used to investigate how changes in the front surface plasma scale length affect fast electron generation and hence the subsequent rear surface ion acceleration. A full author list will be presented as part of the contribution.

8079B-43, Session 10

Dosimetry and biological effectiveness of laser-accelerated particle beams

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Research in Oncology (Germany); E. Beyreuther, T. Burris-Mog, T. Cowan, Forschungszentrum Dresden-Rossendorf e.V. (Germany); Y. Dammene, W. Enghardt, L. Laschinsky, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); E. Lessmann, Forschungszentrum Dresden-Rossendorf e.V. (Germany); M. C. Kaluza, Friedrich-Schiller-Univ. Jena (Germany); S. Kraft, J. Metzkes, Forschungszentrum Dresden-Rossendorf e.V. (Germany); D. Naumburger, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); M. Nicolai, Friedrich-Schiller-Univ. Jena (Germany); C. Richter, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); R. Sauerbrey, Forschungszentrum Dresden-Rossendorf e.V. (Germany); H. Schlenvoigt, Friedrich-Schiller-Univ. Jena (Germany); U. Schramm, Forschungszentrum Dresden-Rossendorf e.V. (Germany); M. Schürer, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); M. Sobiella, Forschungszentrum Dresden-Rossendorf e.V. (Germany); J. Woithe, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); K. Zeil, Forschungszentrum Dresden-Rossendorf e.V. (Germany); J. Pawelke, OncoRay - National Ctr. for Radiation Research in Oncology (Germany)

Purpose: Before laser particle accelerators can be used for radiation therapy, the supply of stable, reliable and reproducible beams with sufficient particle intensity and useable energy spectra is required. Moreover, consequences on dosimetry as well as on radiobiological effectiveness have to be investigated for laser-accelerated and therefore ultra-shortly pulsed particle beams with very high pulse dose rate.

Method and Materials: In vitro cell irradiations have been established and performed within the German multi-institutional research project onCOOPtics for both laser-accelerated electron and proton beams. The experimental setups at two lasers, the 10 TW JETI laser for electron and the 150 TW DRACO laser for proton beams, includes a dedicated system for routine cell sample irradiation and precise determination of applied dose. After extensive tuning and optimization of the laser systems and particle beams as well as test and calibration of all dosimetric components, systematic radiobiological experiments with several tumor and normal tissue cell lines have been performed over the last three years measuring dose-effect-curves for cell survival and DNA double strand break induction.

Results: No significant differences in biological effectiveness between laser-accelerated and conventional electron beams were found, apart from one cell line at one end point. The evaluation of the recently finished proton irradiation campaign is in progress.

Conclusion: Laser accelerators can be used for radiobiological experiments, meeting all necessary requirements like homogeneity, stability and precise dose delivery. Nevertheless, before fulfilling the much higher requirements for clinical application, several improvements concerning i.e. proton energy, spectral shaping and patient safety are necessary. Supported by BMBF (03ZIK445).

8079B-44, Session 11

Applications of laser accelerated particle beams for radiation therapy

C. C. Ma, Fox Chase Cancer Ctr. (United States)

Recent advances in laser technology have made proton (ion) acceleration possible using laser induced plasmas. In this work, we report our work on the investigation of a new proton therapy system for radiation oncology, which employs laser-accelerated protons. If successfully developed, the new system will be compact, cost-effective and capable of delivering energy- and intensity-modulated proton therapy (EIMPT). We have focused our research on three major aspects: (1) target design for laser-proton acceleration, (2) system design for particle/energy selection and beam collimation, and (3) dosimetric studies on the use of laser-accelerated protons for cancer therapy. We have performed particle-in-cell (PIC) simulations to investigate optimal target configurations for proton/ion acceleration. We also performed Monte Carlo simulations to study the beam characteristics and the feasibility of using such beams for cancer treatment. A fast dose calculation algorithm has been developed for pre- and post-optimization dose calculation. Since laser-accelerated protons have broad energy and angular distributions, which are not suitable for radiotherapy applications directly, we have designed a compact particle selection and beam collimating system for EIMPT beam delivery. We also proposed a new gantry design to make the whole system compact and easy to operate with adequate shielding considerations. Our Monte Carlo results show that EIMPT using laser protons provided superior target coverage and much reduced critical structure dose and integral dose. EIMPT is more dosimetrically advantageous than photon IMRT or conventional proton beams.

8079B-45, Session 11

Laser ion accelerators for hadron therapy: requirements and prospects

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We discuss the main parameters of the proton and carbon ion beams required by the hadron therapy. We consider two types of the dose delivery systems: the passive dose delivery system and the active dose delivery system. Passive dose delivery system means the simultaneous irradiation of a whole target (or irradiation of the most part of the target) by a wide ion beam. Active dose delivery system corresponds to a consecutive irradiation of the target voxels by the narrow proton or ion beam using the 3D raster-scan or spot technique. We note a substantial difference between the ion beam parameters required for different dose delivery schemes, passive dose delivery system or active dose delivery system. We propose two schemes of all optical active dose delivery and passive dose delivery systems using the laser accelerated ion beams.

8079B-46, Session 12

Radiobiology with laser-accelerated quasi-monoenergetic proton beams

A. Yogo, T. Maeda, T. Hori, H. Sakaki, K. Ogura, M. Nishiuchi, A. Sagisaka, P. R. Bolton, K. Kondo, Japan Atomic Energy Agency (Japan)

Growing interest in the application of laser-driven ion accelerators for ion beam radiotherapy is attributed to the potential for downsizing both the size and cost of such medical facilities. Investigations of the biological effects of the high bunch current and short bunch duration, that are typical of laser-acceleration, have been reported [1]. These previous works have used proton beams of broad energy spread. To better understand radiobiological effects, it is critically important to use quasi-monoenergetic beam irradiation in these investigations. We report the development of a laser-driven quasi-monoenergetic proton beam transport system, of ~25% energy spread, and subsequent irradiation of human cancer cells using miniature permanent magnets.

The experiment was performed using the J-KAREN laser system at JAEA. Laser pulses are focused to an intensity of 5×10^19 W/cm^2 onto a polyimide foil target of 7.5-μm thickness. The emitted proton spectrum is continuous up to a maximum energy of 4 MeV. Energy selection for transport to cancer cells is determined by four pairs of dipole magnets (quadruple-dipole magnets, QDM), which had been simulated by Luo et al. [2] in their design of a laser-driven therapy machine. Each dipole magnet consists of a pair of permanent magnets generating a central magnetic field of 0.78 T. The second and third magnetic fields are oriented antiparallel to the first and fourth ones. Protons are steered by the first magnetic field, and again by the second one, such that transmitted proton trajectories in the middle of the QDM are shifted laterally from the target normal axis by an energy-dependent displacement. Proton energy and energy spread are selected by a pinhole in this middle plane located between the second and third dipole magnets and subsequently steered downstream by the other two dipole magnets.

We have successfully obtained 2.25 MeV proton beams with an energy spread of 0.66 MeV (FWHM) and single bunch duration of 20 ns. The beams were extracted from vacuum into air through a thin-foil window

and used to irradiate in-vitro cell samples from a human salivary gland tumor. The dose given in a single proton bunch was 0.2 Gy, hence, the single bunch dose rate is estimated to be 10^7 Gy/s. At the 1 Hz repetition-rate cell samples were irradiated with successive proton bunches with integrated dose levels up to 8 Gy (40 shots). Using a colony formation assay, we determine the relative biological effectiveness (RBE) of this proton irradiation for cell inactivation. X-rays delivered from a 4-MV clinical linac were used as reference radiation. RBE at the 10% surviving rate was evaluated to be 1.20±0.11 for the laser-accelerated protons having a volume-averaged LET of 17.1±2.8 keV/μm. We compare our results with published ion beam RBE using conventional accelerators. We also discuss future prospects for radiobiological studies with an upgraded QDM beamline.

[1] A. Yogo et al., Appl. Phys. Lett. 94, 181502 (2009); S.D. Kraft et al., New J. Phys. 12, 085003 (2010)

[2] W. Luo et al., Med. Phys. 32, 794 (2005)

8079B-47, Session 12

Proton source development and radiobiology applications within the LIBRA project

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In view of their properties, laser-driven ion beams have the potential to be employed in a number of innovative applications in the scientific, technological and medical areas. Among these, a particularly high-profile application is particle therapy for cancer treatment, which however requires significant improvements from current performances of laser-driven accelerators. The focus of current research in this field is on developing suitable strategies enabling laser-accelerated ions to match these requirements, while exploiting some of the unique features of a laser-driven process.

LIBRA is a EPSRC-funded UK-wide consortium, aiming to address these issues, and develop laser-driven ion sources suitable for applicative purposes, with a particular focus on biomedical applications. We will report on the activities of the consortium aimed to optimizing the properties of the beams, by developing and employing advanced targetry and by exploring novel acceleration regimes enabling production of beams with reduced energy spread.

The perspective of their future use in cancer therapy demands extensive testing of the biological effects of laser-driven beams, which have very different properties and potentially different radiobiological effectiveness from conventional RF beams. Employing the TARANIS Terawatt laser at Queen's University, we have initiated a campaign investigating the effects of proton irradiation of biological samples at extreme dose rates (> 109 Gy/s). Dispersion of the broadband laser driven multi-MeV proton beam by using a magnetic system, allows simultaneous irradiation of a number of cell spots with different doses on a ns timescale. Consistent lethal effects on V-79 cells have been observed.

8079B-48, Session 12

A technology platform for translational research on laser driven particle accelerators for radiotherapy

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It is widely accepted that beams of protons or light ions may have a high potential for improving cancer cure by means of radiation therapy. However, at present the large dimensions of electromagnetic accelerators (cyclotrons and synchrotrons) and beam deliveries (in particular isocentric gantries) prevent particle therapy from being clinically introduced on a broad scale. Therefore, several technological approaches like compact superconducting circular machines, dielectric wall accelerators and laser driven particle acceleration are under investigation.

For treating all tumour entities particle beams with a range of 30 cm in water (which corresponds for protons to an energy of about 230 MeV) delivering a dose rate exceeding 2 Gy/(min l)is necessary. Thus the central technical challenge is the development of a compact laser system delivering such beams.

However further research is required to transfer laser accelerated particle beams to clinical application in radiotherapy, since the therapeutically relevant parameters of laser driven particle beams dramatically differ from those of beams from conventional electromagnetic accelerators: The duty cycle is extremely low, whereas the number of particles and thus the dose rate per pulse is very high. Laser accelerated particle beams show a broad energy spectrum and substantial intensity fluctuations from pulse to pulse. These properties may influence the biological efficiency of such beams and require a completely new technique of beam delivery and therapy quality assurance.

For this in a collaboration between research groups of Dresden (OncoRay and FZD) and Jena (Friedrich-Schiller-Universität and Fraunhofer Institute of Applied Optics and Precision Engineering) the following topics are studied: (i) dosimetry and, (ii) radiobiological effects of laser accelerated particle beams, (iii) solutions for laser driven therapy beam deliveries, and (iv) image based monitoring and in-vivo dosimetry of hadron beams performing positron emission and single photon emission tomography of products following the nuclear interaction between the therapy beam and the atomic nuclei of the tissue.

The promising results of this research and in particular the rapid progress in high intensity laser technology as well as in the understanding the physics of laser particle acceleration require for closing the existing gap in the translational chain between laboratory and clinic. To reach this, a research building is currently constructed on the campus of the University Hospital Carl Gustav Carus Dresden. It will be closely connected to the Department of Radiooncology and host a diode pumped PW laser system delivering an experimental proton beam and, furthermore, a conventional therapeutic proton cyclotron. The cyclotron beam will be delivered on the one hand to an isocentric gantry for patient treatments equipped with in-room PET/CT and on the other hand to an experimental irradiation site. This way the conventional accelerator will deliver a reference beam for all steps of developing the laser based technology towards applicability in radiation therapy.

8079B-57, Poster Session

Comparison of irradiation effects of synchrotron particle beam and laser driven particle beam irradiation in human cancer cell

T. Maeda, Japan Atomic Energy Agency (Japan) and Hyougo Ion Beam Medical Ctr. (Japan); A. Yogo, Japan Atomic Energy Agency (Japan); Y. Demizu, Hyogo Ion Beam Medical Ctr. (Japan); T. Hori, H. Sakaki, Japan Atomic Energy Agency (Japan); Y. Tomoe, Hyogo Ion Beam Medical Ctr. (Japan); K. Kondo, Japan Atomic Energy Agency (Japan); M. Murakami, Hyogo Ion Beam Medical Ctr. (Japan)

The Hyogo Ion Beam Medical Center (HIBMC) was established in May 2001, a leading project of the 'Hyogo Cancer Strategy'. As its major characteristic, both proton and carbon ion beams can be generated. The accelerator is a synchrotron that can accelerate proton and carbon ion beams at a maximum of 230 and 320 MeV/u, respectively, and the maximum ranges in water are 300 and 200 mm, respectively. Three irradiation rooms installed with 45-degree, horizontal/vertical, and horizontal fixed ports can be used for carbon ion radiation biological experiment and therapy, and b 2 gantry rooms can be additionally used for proton beams. Moreover Laser technology to accelerate particle beam therapy, by Japan Atomic Energy Agency (JAEA) advances development now aim to bring innovation to transform conventional

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treatment, and spread the particle beam therapy, taking advantage of the performance of particle beam therapy, proton therapy equipment laser driven Activities are designed to achieve for clinical application to. We have so far, X-ray, proton, and carbon ion beam lines, the laser-driven proton ion beam , has been examined from the standpoint of comparative molecular cell biology of cancer cells to radiation effects. So far, considering the differences in the types of cytostatic effect and the effect of DNA cleavage and on the relevance of Apoptosis studies in each lines irradiated cancer cells. In this presentation we reports on the difference of the irradiation effect in X rays, the proton beam , and the carbon ion beam to the human cancer cell, and it applies on the focus to survival rate after the X-ray, synchrotron proton beam , the synchrotron carbon ion beam, and the laser driven proton is irradiated.

8079B-58, Poster Session

Dosimetry and spectral analysis of a radiobiological experiment using laser-driven proton beams

F. Fiorini, The Univ. of Birmingham (United Kingdom); D. Kirby, Univ. Hospitals Birmingham NHS Foundation Trust (United Kingdom); M. Borghesi, D. Doria, Queen's Univ. Belfast (United Kingdom); J. C. Jeynes, Univ. of Surrey (United Kingdom); S. Kar, S. Kaur Litt, Queen's Univ. Belfast (United Kingdom); K. J. Kirby, M. J. Merchant, Univ. of Surrey (United Kingdom); S. Green, Univ. Hospitals Birmingham NHS Foundation Trust (United Kingdom)

Laser Induced Beams of Radiation and their Applications (LIBRA) is a UK consortium which aims to develop a new type of ion source by shining an ultra intense laser beam onto a small target of metal, plastic, liquid or gas. One of its proposed applications is ion beam radiation therapy for cancer treatment.

So far, several experiments have been carried out to understand whether a laser-driven beam can really be used for radiobiological purpose and in each of these the total dose on the cells was obtained by using multiple laser shots.

The difficulty with these kind of studies is that the very large instantaneous dose rate is a challenge for the commonly used dosimetry techniques, so that other more complex procedures need to be explored.

With this work we aim to present an experiment where the dosimetry procedure to obtain the dose on the cells was obtained using Gafchomic films to have information on dose and partially on energy, and a Monte Carlo code to expand the measured data in order to obtain specific details of the proton spectrum on the cells.

From the spectral analysis we found that the energy of the protons crossing the cell layer was between 0.8 and 5 MeV, the instantaneous dose rate was estimated to be close to 10^9 Gy/s and the maximum delivered dose ~5 Gy. Some survival results are also presented.

8079B-59, Poster Session

Characterisation of a laser-driven x-ray beam for imaging

F. Fiorini, The Univ. of Birmingham (United Kingdom); R. J. Clarke, Rutherford Appleton Lab. (United Kingdom); Z. Najmudin, Imperial College London (United Kingdom); D. Neely, Rutherford Appleton Lab. (United Kingdom); S. Green, Univ. Hospitals Birmingham NHS Foundation Trust (United Kingdom)

Laser Induced Beams of Radiation and their Applications (LIBRA) is a UK consortium which aims to develop a new type of ion source by shining an ultra intense laser beam onto a small target of metal, plastic, liquid or gas. The laser's energy causes intense high energy ionising radiation to be ejected from the surface of the target and the type of radiation emitted depends on the laser characteristics and the dimensions and composition of the target.

With this work we aim to present one of the possible applications of this new kind of radiation source: imaging (medical and non-medical) using laser-driven x-ray beams. The x-ray beam is produced by the fast electrons in the target material, which are generated during the laser-target interaction. In particular, our primary interest lies in studying how the x-ray spectrum changes in dependence of the laser intensity and of the target material and thickness when the electron beam interacts with it.

The simulations presented in this work were performed using Fluka (FLUctuating KAskad), a Monte Carlo code for calculations of particle transport and interaction with matter. Given its aims, Fluka is not meant to simulate reactions produced by lasers, but to a good approximation it can simulate the electron interactions which produce the photon beam.

Using theoretical hot electron spectra, from the simulations, we found that independently on the target material:

- the highest laser intensities (I ≥ 10^21 W/cm^2) produce x-ray beams too energetic to be used for imaging;

- intermediate intensities (10^18 W/cm^2 ≤ I ≤ 10^20 W/cm^2) could be used for container and cargo screening or even for photon therapy;

- the lowest intensities (I~10^17 W/cm^2) could be used for medical imaging, with the very promising possibility of using it during a laser-driven ion therapy session to check the progress of the therapy.

For each intensity, the material and thickness of the target were investigated in order to produce the maximum number of x-rays.

8079B-49, Session 13

Medical applications studies at ELI: nuclear physics

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ELI Nuclear Physics, one of the 4 pillars of ELI, is meant as an unique research facility to investigate the impact of very intense electromagnetic radiation (Extreme Light) on matter with specific focus on nuclear phenomena and their practical applications. The extreme light is realized at ELI-NP in two ways: by very high optical laser intensities and by the very short wavelength beams on γ-ray domain with very high brilliance. This combination allows for stand-alone experiments with a state-of-art high-intensity laser, standalone high resolution γ-beam experiments or combined experiments of both photon sources. The description of the foreseen medical applications studies at ELI-NP will be presented.

8079B-50, Session 13

TBA1

J. Kieffer, Institut National de la Recherche Scientifique (Canada)

No abstract available

8079B-51, Session 13

Pulsed radiobiology with laser-driven plasma accelerators

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Recently, a high efficiency regime of acceleration in laser plasmas has been discovered at CEA-Saclay SLIC laser facility by an European team of scientists. This regime allows table top equipment to deliver doses of interest for radiotherapy with electron bunches of suitable kinetic energy. An experimental facility delivering relativistic electrons from a few MeV up to a few tens of MeV is available at Intense Irradiation Laboratory in Pisa. The National Research Council (Italy) launched an R&D program aimed to the realization of an innovative class of accelerators for medical uses, based on laser techniques

of acceleration. In this framework, a preliminary radiobiological validation is needed. At the present time, the biological effects of electron bunches from the laser-driven electron accelerator are largely unknown. In radiobiology and radiotherapy, it is known that the early spatial distribution of energy deposition following ionizing radiation interactions with DNA molecule is crucial for the prediction of damages at cellular or tissue levels and during the clinical responses to this irradiation. The purpose of the present study is to evaluate the radio-biological effects obtained with electron bunches from a laser-driven electron accelerator compared with bunches coming from a IORT-dedicated medical Radio-frequency based linac's on human cells by the cytokinesis block micronucleus assay (CBMN). To this purpose a multidisciplinary team including radiotherapists, biologists, medical physicists, laser and plasma physicists is working at CNR Campus in Pisa. The team provides a complete spectrum of expertise from radiotherapy of tumors to preparation samples, testing of biological effects, dosimetry, set up and control of the high power laser equipment, set up and control of the laser-plasma mini-linac. Dose on samples is delivered alternatively by the "laser-linac" operating at ILIL lab of Istituto Nazionale di Ottica and an RF-linac operating for IORT at Pisa S. Chiara Hospital. Experimental data are analyzed on the basis of suitable radiobiological models as well as with numerical simulation based on Monte Carlo codes. Possible collective effects are also considered in the case of ultrashort bunches of ionizing radiation.

8079B-52, Session 14

Laser-plasma accelerated high-energy electron beams for radiotherapy

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Recent experimental advances of laser-plasma accelerators are applied to radiation therapy. In the interaction between an intense laser pulse and a helium gas jet, beams of quasi-monoenergetic, well collimated and energetic electrons are produced. A secondary, counterpropagating laser beam is used to control the electron injection process and to generate a stable and tunable electron beam with narrow energy spread and ultrashort duration. The potential use of this beam for radiation treatment is evaluated experimentally by measurements of dose deposition of a 120 MeV electron beam in a polystyrene phantom. It is found that the electron beam can deliver a substantial dose (>1 Gy) in a single laser shot by direct irradiation, without the use of intermediate magnetic transport or focusing. Monte-Carlo simulations of electron beam propagation and dose deposition show excellent agreement with the measured data. The dose is delivered in an ultrashort time (<100 fs) and with exceptionally high peak dose rate (>10^{13} Gy/s). The impact of such extreme radiation conditions on living cells is briefly discussed.

8079B-53, Session 14

Prospects for medical applications of proton- and x-ray beams produced with ultra-fast CO_2 lasers

I. V. Pogorelsky, M. N. Polyanskiy, V. Yakimenko, Brookhaven National Lab. (United States); Z. Najmudin, Imperial College London (United Kingdom); P. Shkolnikov, Stony Brook Univ. (United States); P. Oliva, M. Carpinelli, Univ. degli Studi di Sassari (Italy); I. Ben-Zvi, Brookhaven National Lab. (United States)

We describe the principles of emerging ultra-fast, long-wavelength laser technology. It is based on converting picosecond pulses, generated in the near-IR (lambda~1 um) by solid-state lasers, to the mid-IR (lambda~10 um) and amplifying them in high-pressure CO2 amplifiers to reach relativistic intensities. Our recent progress in using such lasers in Thomson scattering and ion acceleration experiments underlines the promising potentials of this technology for enabling sources of secondary radiation and particles for medical and biological applications. These experiments capitalize on particular advantages of long-wavelength lasers, such as their high number of photons per energy unit, and their beneficial wavelength- scaling of the electrons' ponderomotive energy and critical plasma frequency.

Our recent proof-of-principle ion acceleration experiment produced a 1.2 MeV proton beam with a narrow energy spread of only ±4% (Fig.1) from a supersonic hydrogen jet using a 1-TW CO2 laser. The experiment's impressive features are the monoenergetic beam we generated, and the low power of the CO 2 laser we used; its intensity was a hundredfold lower than the minimum required for obtaining ~1 MeV protons with a solid-state laser. This ATF experiment met all conditions for a new method of accelerating ions, viz., Radiation Pressure Acceleration (RPA): The circular polarization of the laser beam; the occurrence of the effect close to the critical gas density: and especially, the monochromaticity of the spectrum. The advantage of the RPA mechanism lies in the favorable linear scaling of the ions' energy with the laser's intensity. This excellent power scaling will engender a very compact accelerator generating high-energy hadrons, whilst the gas jet should assure good control over the repetition rate and purity of the produced beams. In addition, the RPA mechanism can produce monoenergetic hadron beams. The outcome of this experiment allows us to draft a roadmap towards higher proton energies (>200 MeV) via the laser upgrade, and to plan a full-energy, high-dose hadron therapy facility.

In other series of experiments, we employed the same CO2 laser, combined with a relativistic electron- beam from the 70-MeV linac, for generating x-rays via Thomson scattering and investigating the applicability of such a source for biological imaging. To capture, in a single shot, a high-resolution x-ray image of a live object, four parameters especially are important: Short duration pulses; small source; high proton-flux adequate for detecting with realistic imaging techniques; and, high monochromaticity. These features of the ATF's x-ray source were verified experimentally and enabled us to demonstrate the single-shot phase-contrast imaging of fine biological details with a 1 ps exposure.

We expand upon the possibility of multiplying the repetition rate of the X-ray source via recycling the laser pulse in a closed-loop amplifier cavity.

8079B-54, Session 14

Proton acceleration to above 6MeV by interaction of 1017W/cm_2 laser pulse with H_2O nano-wire targets

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We report on experimental demonstration of fast protons (>6 MeV) generated by interaction of modest laser intensities (~1017 W/cm2) with micro-structured H2O (snow nano-wire) targets. Recently we have demonstrated very efficient coupling of laser energy to snow nano-wires grown on a Sapphire substrate [1] and the generation of fast multi-charged Oxygen ions measured using x-ray emission spectra [2]. Here we report on measurements of protons with energies above 6 MeV generated from a snow-wire target grown on a Sapphire substrate and irradiated with relatively modest laser intensity (1017 W/cm2). These were measured using CR39 stacks and various filters. Usually, protons at these energy levels are measured when various targets such as thin-foils or gas jets are irradiated by high intense laser beams, I>1018 W/cm2. In the scheme presented in this work we have used lower intensities. The protons were accelerated backward mainly along the target normal direction. Protons with energies above 6 MeV were recorded. The snow target combined of H2O shaped as a nano sized elongated wires with characteristic diameter in the range of 0.01-0.1µm and length of several m. We are planning to extend our study to much higher laser intensity in order to scale the proton energies to tens of MeV.

The ability to generate fast proton from small and relatively inexpensive systems is of great importance to many applications such as medical radiation treatments and others. The presented scheme of using snow nano-wires can relieve the demand for very high laser intensities, thus reducing the size and the cost of laser system, bringing us closer to the goal.

1. Generation of fast ions by an efficient coupling of high power laser into snow nanotubes Palchan, T; Henis, Z; Faenov, AY, et al. Appl. Phys. Lett. 91 251501, 2007

2. Application of Snow Nanograin Targets for the Generation of Fast Ions in Femtosecond Laser Plasma Faenov, AY; Magunov, AI; Pikuz, SA, and A.Zigler J. Exp. and Theor. Phys. 107 351-355 2008

8079B-55, Session 15

Potential medical applications of laser generated particles

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The use of high energy laser beams on specially designed targets of various chemical compositions has many potential advantages in cancer therapy, including the:-

1. production of a wide range of ion species either alone or in combination, with rapid changes in choice of protons or other ions,

2. presence of concomitant -rays in low dose for imaging purposes,

3. high dose rates for patient throughput,

4. choice of target shape to give required range of energies to match at least some or most of the tumour 3-D geometry.

5. delivery of laser light by mirror deflection to different treatment rooms and to relatively small gantries near to the patient.

The competition faced by lasers in this field is considerable: modern cyclotrons and synchrotrons provide adequate treatments, but at high cost. Cyclotrons, so far, cannot accelerate heavier charged particles to clinically useful energies; synchrotrons are slow cycling and treatments take longer. For both, the cost of gantries is considerable and there remains only one gantry in the world capable of delivering carbon ions at any angle of trajectory to a patient. Proton gantries appear to cost as much as a cyclotron itself.

In order for laser generated particles to be clinically acceptable and become the method of choice, we must overcome several problem areas. These include being able to provide:-

- Accurate and reliable numbers of specified particles at the required energies or ranges of energies

- A reasonably fast repetition rate

- Convincing demonstrations of being able to ‘dose paint’ a variety of tumours of different linear dimensions and at variable depths within humanoid phantoms to the tolerance level required in clinical practice.

- Ultra high dose rates to only parts of the tumour with sufficient time before the next exposure to the same part - to allow re-diffusion of oxygen back into hypoxic zones which can be made more hypoxic by rapid depletion of oxygen.

- Optimum angular trajectories, but little or no beam contamination with unwanted particles such as neutrons.

- Automation of all the above features.

Laser generated particle production will be worthwhile in the clinic as long as the above issues can be solved by further research.

8079B-56, Session 15

Novel technologies in charged particle therapy

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Charged Particle Therapy (the use of protons and other light ions such as carbon to treat certain forms of cancer) is experiencing a rapid expansion in many parts of the world, and there are now more than 30 such centres operating in hospitals. The current technologies available use cyclotrons and synchrotrons to deliver the dose to the cancer. While each of these technologies is mature, and capable of treating cancer successfully, there is always room for improvement in technique, to reduce costs, increase throughput and availability and improve outcomes. This talk will discuss some recent development, using both traditional and laser-based accelerator techniques.

Conference 8080A: Diode-Pumped High Energy and High Power Lasers

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8080A-01, Session 1

Optical properties of CaF_2 and Yb^{3+}:CaF_2 for laser applications

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Highly transparent CaF2 has found many applications from the deep UV- to the IR-range. The optical quality and the laser damage threshold are influenced by the purity and the real structure of the crystal. Both properties strongly depend on raw material quality and growth conditions.

Production of pure CaF2 single crystals and their characterization are described. The authors´ process enables to produce crystals up to diameters of 350mm with an internal transmittance of higher than 99.7% at 193nm (thickness 100mm) and a homogeneity of refractive index below 1ppm for diameters >200mm.

A new approach is the growth of Yb3+ doped CaF2 crystals in such furnaces dedicated to large volumes. The advantage of higher volume is the better homogeneity of the dopant concentration in the crystal. Critical mechanical properties especially of the doped fluoride have to be taken into account. The growth process has to be adopted carefully to avoid stresses, cracks and other crystal defects.

Data of refractive index homogeneity and stress birefringence are presented. A comparison of doped and undoped crystals is made and an outlook for further improvement is given.

The segregation coefficient of the dopant which is important to be near to one is reported. The ratio Yb3+ /Yb2+ is characterized spectroscopically. Differences between top and bottom of the crystal are shown.

Results of the real structure evaluation are presented. The most critical feature for high energy applications which are strength and concentration of small angle grain boundaries are compared with that of undoped crystals.

8080A-02, Session 1

Temperature dependent measurement of absorption and emission cross sections for various Yb^{3+} doped laser materials

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In the last years Yb3+ doped gain media have gained more and more importance for high energy diode pumped solid state systems. A long fluorescence lifetime and a low quantum defect are promising high efficiencies for laser operation. At room temperature reabsorption is strongly limiting the possible efficiency of short pulse laser amplifiers, which can be overcome when operating at low temperatures. In this work we provide temperature dependent emission and absorption cross section measurements for various Ytterbium doped media including Yb:YAG, Yb:CaF2 and Yb:FP15-glass from room temperature down to 100K in steps of 20K. Based on these measurements we also present simulation studies on the amplifier performances. The cooling of the samples was performed with a liquid nitrogen driven cryostat allowing a free temperature adjustment within the range from 100K to 300K. In order to avoid condensation on the sample surface the cryostat was evacuated to a vacuum with pressures in the range of 10-6mBar. All spectral measurements were performed with a fiber coupled scanning spectrum analyzer, providing a spectral resolution down to 0.05nm. This allows to analyze sharp spectral peaks with a proper resolution. The absorption spectra were obtained from measuring the transmission of a fiber coupled white light source which was imaged through the sample and afterwards reimaged to the spectrometer fiber. The absorption cross sections were then determined by applying Lambert Beer's law. For measuring the fluorescence spectra with only small influence of reabsorption a 10W fiber coupled diode was focused onto the sample surface for pumping, while the fluorescence light emitted under an angle from the same side of the sample was again imaged into the spectrometer fiber. Due to this setup only the fluorescence light originating from a small area close to the surface is measured. Therefore the error coming from amplified stimulated emission and absorption is minimized. The emission spectra were retrieved with the Mc Cumber Relation using the absorption cross sections. In comparison the Füchtbauer Ladenburg method was employed for a direct calculation of the emission cross section out of the fluorescence spectra. Since both methods are only valid in a limited spectral range the results were than combined in order to obtain a valid emission cross section over the whole range of interest. We also present a simulation tool for a numeric solution of the laser rate equations also in the case of Ytterbium. The model includes all necessary parameters such as pump fluence and duration, total gain and temperature. Finally together with the estimated efficiencies for cooling a prediction of the optimum operating temperature is presented with respect to the global laser efficiency for each material.

8080A-03, Session 1

Broadband, diode-pumped Yb:SiO_2 multicomponent glass laser

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The interest in Yb3+-doped laser materials and their utilization in solid-state lasers is unbroken. Due to their low quantum defect, absence of excited state absorption or quenching effects ytterbium-doped gain media are preferred for diode-pumped lasers operating around 1 µm. When scaling a diode-pumped short-pulse laser to high output pulse energies (i.e. 10 J and higher) large aperture gain media are required. Despite of their favorable material parameters most crystals still cannot be utilized in high energy lasers due to their limited maximum size at crystal growth. Although some ceramic materials such as YAG with large aperture dimensions have already been demonstrated the utilization of centimeter sized laser glasses is still a promising approach especially for high energy, ultrashort pulse lasers due to the broad emission bandwidth. The huge advantage of the here presented multicomponent fused silica glass as gain material is its fabrication technique. It can be produced directly out of a glass melt with large active volume and high optical quality.

Here we present first lasing and tunability results of a diode-pumped Yb:SiO2 multicomponent glass laser. The doped glass samples used in the experiments were developed at the Institute of Photonic Technology, Jena. The multicomponent glass consists of 70 mol% SiO2, 20 mol% Al2O3, 9.1 mol% La2O3, and a doping level of 0.875 mol% Yb2O3. The here presented glass samples exhibit a diameter of 15 mm and thickness ranging from 1.5 to 6 mm. Due to the high contingent of SiO2 the spectroscopic properties of the multicomponent glass are similar to Yb-doped fused silica glass. The upper-state lifetime was measured to 0.69 ms which is also in good agreement with doped fused silica values.

The Yb-doped multicomponent glass sample in the experiment had a thickness of 1.5 mm. The sample was polished in laser quality and did not exhibit an AR coating. For pumping a fiber coupled laser diode was used with optical power of 6W at 975nm and pump light absorption was about 60%. In order to increase the pump absorption the non-absorbed pump was re-collimated and reflected back into the Yb:SiO2. The laser cavity was a V-shaped resonator and the folding mirror had a curvature of 200mm. The two cavity arm lengths were set

to 105 mm and 400 mm respectively. This results in a stable confocal resonator with a beam waist of about 50 µm in the glass and 600 µm on the output coupler. The free running laser wavelength was centered around 1055nm. The slope efficiency results in a value of 32%. The output beam had a gaussian shape, but was slightly elliptical due to the angle of folding mirror. The wavelength tunability of the laser cavity was achieved inserting a brewster prism (SF10) in between the folding mirror and the output coupler. The wavelength was adjusted by tilting the OC. At a pump level of 5 W the laser had a tuning range from 1010 nm to 1080nm.

8080A-04, Session 2

Recent advances in diode pump engines for high-power amplifiers

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Based on recent advances in diode laser technology we present experimental results (peak power, brightness, spectrum, beam homogeneity) of several low duty cycle pump modules with 2 to 40kW peak power and discuss its suitability for pumping Yb3+ doped laser materials. We will present a roadmap for low duty cycle pump modules with up to 80kW peak power.

8080A-05, Session 2

Residual mechanical stress decrease in GaAs-based laser diodes via a bi-material investigation

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Bonding-induced stress in GaAs-based laser diodes is studied by numerical and experimental techniques. This stress induced by the soldering processes appears when cooling down the assembly because of Thermal Expansion Coefficient (TEC) mismatches, and dimensional disparities. Detailed mechanisms taking place are not fully understood. Residual stress is also known to influence device reliability.

Composite submounts studied are composed of a CuW heat spreader on an AlN bottom plate in standard and optimized designs to lower mechanical stress level. CuW shows a high thermal conductivity and a matched TEC with GaAs. Plain AlN submounts are studied as a reference.

The numerical technique is a Finite Element Method calculation to compute the stress tensor induced in GaAs-based laser diodes during the soldering process on submounts with 80-20 AuSn eutectic alloy solder pads. A 3D thermochemical model is taken into account. Mechanical boundaries are set at the AlN plate bottom, and the different parts of the geometry are set as bonded (i.e. no separation, translation, nor rotation are allowed between the different objects). The temperature is lowered from AuSn melting temperature (280°C) to room temperature. The plain AlN submount exhibits 31 MPa, while the standard composite submount gives 23.5 MPa and the optimized version is as low as 12 MPa.

The experimental technique consists of photoluminescence (PL) Degree of Polarization (DoP) measurements emitted by a planarized diode bonded to a submount. P-epitaxial layers are removed from laser diodes by chemical etching steps, so that the semiconductor quantum-well is accessible for DoP measurements. Samples are exited by a HeNe laser, through a chopper. The polarized PL components are collected by two detectors after passing trough a polarizing beam-splitter. DoP measurements are performed according to the well-established experimental method from Paul D. Colbourne et D. T. Cassidy [1]. In our study, the planarized diode top surface is scanned with a 15 µm longitudinal step and a 6 µm lateral one. The raw results are obtained as a matrix, where each component aij is either the PL intensity or the PL DoP at the spatial position defined by (i ; j). DoP and PL intensity are linked to sample stress levels for the stress modifies the semiconductor band gap energy and separates the heavy and light hole bands, influencing the polarized light emission probability along the stress direction . Starting with a normalized DoP of 1 on plain AlN submounts, the standard composite submount gives 0.5 DoP reduction while the optimized version is expected to exhibit a reduction larger than 0.65.

Electro-optical measurements are to be performed on the different devices to estimate the stress level impact on laser diode performances and reliability.

Composite submounts with reduced mechanical stress and preserved thermal properties were studied experimentally and theoretically. An optimized design allows to reduce the mechanical stress by a factor 2.5 at least.

[1]. Paul D. Colbourne et D. T. Cassidy, « Imaging of stresses in GaAs diode lasers using polarisation-resolved photoluminescence », IEEE Journal of Quantum Electronics, vol. 29, no. 1, p. 62-68, January 1993.

8080A-06, Session 2

The Petawatt-Field-Synthesizer (PFS) project at the MPIQ

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The Petawatt-Field-Synthesizer (PFS) project at the Max-Planck-Institut für Quantenoptik (Garching) aims at developing a light source delivering Petawatt-scale carrier-envelope phase controlled pulses with pulse energies > 3J in the few-cycle regime (< 5fs, 700...1400nm) at a repetition rate of 10 Hz. The concept for reaching the ambitious parameters of PFS is based on the optical parametric chirped pulse amplification (OPCPA) technology on the few-ps scale.

Therefore a special, synchronized pump delivering 1-2ps pulses with 4×5J pulse energy (frequency doubled at 515 nm) i.e. 4×12J in the fundamental beam (1030nm) at 10Hz repetition rate is required. Here we present our latest achievements in building this CPA pump source which is based on diode-pumped, Yb-doped amplifiers.

To ensure best synchronisation between the pump laser chain and the OPCPA chain, both were seeded by the same frontend. For seeding the CPA pump laser a small part of the frontend oscillator gets spectrally shifted in a photonic-crystal fiber. The spectral part around 1030nm is filtered out and then amplified in 2 subsequent fiber amplifiers. A grating stretcher stretches the pulses from 4.4ps to 3ns with a spectral throughput of 4nm at a center wavelength of 1030nm. A Dazzler enables spectral phase -and amplitude shaping of the pulses and hence suppress the effect of gain narrowing in the subsequent Yb:YAG amplifiers.

The first amplification stage after stretching is a regenerative Yb:Glass amplifier pumped by a 5W fiber-coupled diode operating at 976nm and 10Hz repetition rate. In approx. 100 roundtrips the pulse energy is raised to 180µJ without influencing the spectral shape. An 8-pass Yb:YAG amplifier serves as second amplification stage. The Yb:YAG crystal rod (dia. 6mm x 8mm, 3%-doped, AR-coated) is pumped by a diode-laser stack with a maximum output power of 4kW (quasi-cw) at a center wavelength of 940nm. The turning mirrors are positioned in such a way that every pass has the same diameter of 2.5mm in the Yb:YAG crystal. The output energy of this amplifier is 300mJ at 10 Hz repetition rate while the spectral bandwith is slightly reduced to 3.5nm. We succeeded in compressing these pulses down to sub-900fs with an efficiency of 66%.

8080A-07, Session 2

Development of a 10 mJ-level optically synchronized picosecond Yb:KYW amplifier at 1040 nm for OPCPA pumping

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We report the results on a novel 10 mJ-level diode-pump Yb:KYW amplifier at 1040 nm. This amplifier operates in the picosecond regime with a repetition rate of 10 Hz. It will be used in the front end of a petawatt laser system for pumping an optical parametric chirped pulse amplifier (OPCPA) for contrast enhancement. For the synchronization purpose the amplifier is seeded by pulses that are derived from the femtosecond oscillator of the petawatt laser system. After amplification in a double stage fiber amplifier the pulses are injected into the Yb:KYW regenerative cavity. Finally, the pulses are compressed to 1 ps before second harmonic conversion in order to achieve a high contrast with the parametric amplification sage.

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8080A-08, Session 3

Simple model to explain instabilities in passively-phased fiber laser arrays

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In theory, passively phased fiber laser arrays hold greater promise than actively phased arrays as they do not require the extra optics and electronics for measuring and controlling the phase of the emitted fields, and there could be an additional advantage in the maximum power capacity per emitter. On the other hand, existing passive systems are limited in the number of elements they can efficiently combine, which has its origin in inevitable internal optical path differences of the active lasers and of external links. In the investigation reported here we show that additional limits are anticipated due to instabilities inherent in the dynamics of passively phased systems, i.e. the pulsation instabilities that have been reported in some experiments, which we suspect to be of the nature of those we predict. To explain these observations we first propose a simple physical model based on the following features: (a) nonlinearity that is inherent in the amplifying media, and (b), the great sensitivity of passively phased systems of the feedback efficiency to fluctuations in phase. Due to these features we anticipate an unstable feedback loop at sufficiently high levels of internal field intensity in arrays having more than a single element (N>1). To verify this model we solved an authentic, physically representative system of space-time dependent nonlinear propagation equations for the optical fields subject to boundary conditions in which these fields are coherently coupled, and rate equations for the gain media. Although the mathematical model represents a ring cavity configuration, its validity is much broader. This mathematical model is designed to give a faithful representation of the dynamics, of the relaxation oscillations in particular. Our traditional method investigated the stability of fixed point (C.W.) solutions by means of first-order perturbation theory, yielding oscillation frequencies and relaxation rates of modes up to high order (about 500), but not all orders. In the absence of Kerr and gain-related nonlinearities (by Kramer-Kronig relations), we predicted the presence of damping of all relaxation oscillations thus calculated. They also continued to be damped at low operation levels when the correct non-vanishing values of the nonlinear constants were assumed, but at higher levels an increasing number of low-loss cavity modes of all N>1 systems investigated became unstable, where N is the number of emitters. The power levels in the transition region agreed with expectations based on experiments, and were found to occur at higher levels for N=2 than for N=3, which is the largest array we have attempted to compute to-date. This also agrees with predictions of analytical results. We conclude that dynamic instabilities can be mitigated by minimizing nonlinear effects in the same way as traditionally attempted for the improvement of steady-state performance (e.g. fiber design, counter-pumping, etc.), and in addition we will call attention to other improvements that can be implemented. This research effort was funded by the Air Force Office of Scientific Research (AFOSR) and the High-Energy Laser Joint Technology Office (HEL-JTO).

8080A-09, Session 3

Laser phased-array beam steering based on crystal fiber

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No abstract available

8080A-10, Session 4

One kilohertz cryogenic disk laser with high average power

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The development of high average and peak power laser is one of the most significant directions of quantum electronics. One of the main problems limiting average laser power is the heat release in the active elements (AE), which leads to negative thermal effects. Yb:YAG crystals are often used as AE dopant because of a small quantum defect ~9%, a long lifetime (~1ms) and absence of an absorption from the excited level. One more remarkable method of improvement laser and thermo optical characteristics is cooling AE up to liquid nitrogen temperatures. At cooling the heat conductivity, emission and absorption cross sections are increased, the thermal expansion, dn/dT and ions density of the lower laser level are decreased. Due to effective heat removal and weak self-focusing thin disk lasers are one of the most perspective high capacity and average power lasers. For today output parameters of thin disk lasers has reached sub-kW average power and hundreds mJ of pulse energy.

New results of high capacity and high power cryogenic disk laser development in the IAP RAS (Nizhniy Novgorod, Russia) are presented in this work. The signal (3 (5) mJ in 200ps (20ns) pulse at 1kHz repetition rate) from the master oscillator (MO) was amplified up to 40mJ after 16-pass preamplifier (PA) and will be amplified up to 0.5J after 8-pass 2 disks main amplifier (MA). The average output power of the laser system will be 0.5 kW at the total pump power about 3kW at 940nm wavelength.

Spectral and thermooptical properties of Yb:YAG(10%) crystal are investigated in this work. It is shown, that cooling from 300K to 80K results to emission cross section increasing by factor of 5. But it leads to shift of wavelength of maximal emission cross section from 1030.1nm to 1029.3nm and reduction of emission cross section width up to 1.3nm. So, it is necessary to adjust the seed laser wavelength with maximal amplification of cryogenic amplifiers system. Absorption of laser radiation at 1029.3nm was measured at 80-300 K temperature range. These measurements shows that the system of laser levels in Yb:YAG(10%) goes from quasi three-level to four-level system only at temperature below 150K. Also thermooptical constants P and Q and thermooptical anisotropy parameter was measured. These material constants completely determine a thermal depolarization and a thermal lens in a disk at known a heat emission intensity and heat conductivity.

The numerical model for stored energy calculation in Yb:YAG disk active element with diode pump was developed. Theoretical calculations have a good agreement with small signal gain measurements in cryogenically cooled Yb:YAG disks. The basic limiting factors of high capacity cryogenic disk laser (amplified spontaneous emission ASE and parasitic generation) are investigated. Was experimentally shown that in beveled Yb:YAG disk the parasitic generation threshold was significantly increased in comparison with Yb:YAG disk. The best geometry from the point of view of ASE and parasitic generation reduction is Yb:YAG/YAG sandwich. It is theoretically shown, that it is possible to store more than half of absorbed pump energy in such element.

8080A-11, Session 4

Heat deposition in cryogenically cooled multi-slab amplifiers

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To evaluate parameters of high average power 100 J, 10 Hz HiLASE and 500 J, 10 Hz ELI cryogenically cooled multi-slab amplifiers, a numerical model of the amplified spontaneous emission and the heat deposition within crystal slabs has been developed.

In the model photons from a homogenous pump source are absorbed in the Yb:YAG crystal creating excited ions and population inversion. The excited ions spontaneously emit photons. These photons are generated by the Monte Carlo method and are ray-traced in a homemade MATLAB code. The number of photons in each ray upon propagation is changed by stimulated emission (ASE) or absorption. The population inversion in each pixel is changed accordingly. The rays are ray-traced until they leave the crystal through front or back faces or are absorbed in side faces of the crystal made of index matched highly absorptive material. The highly absorptive material is necessary for limiting reflections and ASE. Due to low temperatures (175 K) the thermal population of the lower laser level is negligible and the crystal can be modeled as a four-level system with no re-absorption.

According to calculations, nearly 50% of the pump energy can be stored in the gain medium while the rest of the energy is carried away by spontaneously emitted and amplified photons. From these photons less than 10% exit the amplifier, while around 90% are absorbed in side faces where they act as an intensive heat source. In agreement with usual asumptions, quantum defect and absorbed photons change 10% of absorbed energy into the heat in the pumped volume of the crystal, but almost 54% of the absorbed energy is deposited as heat in the side faces increasing the heat generation in the crystal above usual considerations. Moreover, the heat energy deposition in the side faces is not homogenous. The peripheries of the slab side faces generate 20% more heat than the central parts.

This non-uniformly deposited heat in the sides of the slab can create internal stress in the crystal. To prevent heat accumulation in the sides of the crystal, we propose to add a special absorptive layer separated from the slab by thermally insulating substance.

8080A-12, Session 4

High-efficiency, relay imaging, diode-pumped amplifier for nanosecond pulses

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We present gain measurements with different Ytterbium doped gain media, such as Yb:YAG, Yb:FP15-glass and Yb:CaF2 in a multi pass amplifier setup. The temperature of these materials was adjusted freely between 100K and 300K, while heat removal was done by transverse cooling. Condensation on the surface of the laser materials at low temperatures was prevented by placing the crystal in a vacuum chamber, with pressures in the high vacuum range. In order to obtain a good beam profile throughout the amplification process we used a mirror based relay imaging setup consisting of a mirror telescope with 4f-imaging. In a cavity between two planar end mirrors a wandering of the beam on the spherical mirrors after every roundtrip was realized. The active medium was set into one image plane. By tilting one of the plane end the number of round trips in the cavity was adjusted. The astigmatism caused by the angle of incidence of 12° on the spherical mirrors, was compensated by introducing the same amount of astigmatism also in the opposite orthogonal direction. The cavity length was then aligned with respect to the reduced focal length. Due to this compensation of the astigmatism the number of amplifier round-trips had little impact on the extracted beam profile. The beam quality of the amplifier was only limited by the pump profile of the pumping diodes. Each material was pumped by two laser diode stacks with 2.5kW peak output power each. Due to the damage threshold fluence the output energy of the amplifier was limited to about 1J at a beam diameter of 4 mm FWHM. The seed pulses with a duration of 6 ns were generated in a Yb:FP15-glass cavity dumped oscillator. Further amplification to the 100mJ level was provided by a room temperature Yb:YAG multi pass amplifier. The 1 Hz repetition rate of the system was limited by the maximum repetition rate of the front-end. The performance of the main amplifier was monitored over the whole temperature range and for different configurations. For example, with Yb:YAG we achieved an output energy of 1.1 J and an optical-to-optical-efficiency of more than 45%.

8080A-13, Session 5

Z-Backlighter facility upgrades: a path to short/long pulse, multi-frame, multi-color x-ray backlighting at the Z-Accelerator

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Since 2001 the Z-Backlighter facility at Sandia National Laboratories has been operating the Z-Beamlet laser (ns, kJ class at 527nm) in order to radiograph high energy density physics (HEDP) events at the center of the Z-Accelerator. In recent years our facility has added a short pulse laser capability called Z-Petawatt (ZPW) which operates at 0.5ps, 500J and 1054nm. This system will be able to create x-ray backlighting energies >25keV which will allow us to probe deeper into the HEDP event whereas the reduced pulsewidth will significantly improve motion blurring. We report here on several upgrades to our laser and facility that are presently pursued:

A new OPCPA pump laser has been commissioned which operates at 2Hz, 5J, and 532nm. This system will pump a new 4-stage OPCPA system that is scheduled to replace the current 3-stage system next year. Modeling suggests that > 1J of 1054nm should be achievable in a bandwidth of 16nm.

The current ZPW laser is limited by the damage threshold of the final gold compression gratings. Multilayer dielectric gratings are currently being fabricated at 94cm x 42cm size. This should yield about one kJ of short pulse energy and > 1.5kJ at 10ps.

Efforts are underway to beam-combine the Z-Beamlet and ZPW laser for advanced backlighting at the Z-Accelerator. This would allow for short/long pulse, multi-frame exposure at different x-ray energies. To that extend, damage test studies have been performed on dichroic beam (1054nm/ 527nm, 532nm) combination optics.

Laser-target interaction experiments are currently performed at the 100TW subsystem of ZPW. A new target area has been built that will house three target chambers for Z-Beamlet only and one target chamber for ZPW with optional beam combination with Z-Beamlet.

These upgrades are expected to be completed within the next years and should greatly enhance the flexibility and usability of our facility which will undoubtedly benefit the broader HEDP community.

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8080A-14, Session 5

Contrast improvement by prepulse suppression of cascaded amplifier cavities

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The intensity contrast of high-energy lasers is a crucial parameter in high-intensity laser-matter experiments. To avoid ionization and heating processes induced by prepulses the contrast has to be as high as possible. The intensity contrast $\eta(t) = I(t)/I0$ is defined as the ratio between the momentary intensity I(t) at time t before or after the arrival of the main pulse which reaches a peak intensity I0.

High energy short-pulse laser systems often consist of an oscillator and a certain number of regenerative amplifiers. The repetition rate of such laser systems is some orders of magnitude lower than the repetition rate of the oscillator. Pulse picking systems employing the technique of polarization gating are widely used for this purpose.

Due to the limited extinction ratio of the polarizers and the remaining birefringence of the PC, the polarization contrast of a pulse picker could practically not be increased beyond a certain value. A small part of the pulse train (~ 10^−3) will leak into the subsequent amplifier cavity. Considering one pulse before the amplified main pulse, the time difference (Δt) between the main pulse and the considered prepulse can be calculated by Δt = Δtc1 - Δtc2, where Δtc1 comprises the round trip time of the first and Δtc2 of the second amplifier cavity. The considered prepulse passes the amplifier once and is temporally located before the main pulse if Δtc1 > Δtc2 and behind the main pulse if Δtc1 <Δtc2. Considering a pulse train before and after the amplified main pulse, prepulses are to be expected in both cases.

At the Polaris system the round trip times of the first and second regenerative amplifier is 9.7ns and 12.6ns, respectively. The first amplifier produces a pre- and postpulse train due to the limited extinction ratio of the used Thin Film Polarizer of 10^-2 with a time period equal to the round trip time. The first postpulse of this pulse train arrives at the entrance of the second amplifier 9.7ns after the main pulse. At this time the main pulse has travelled 9.7 ns into the cavity with 2.9ns to go until it reaches the entrance again. Thus, now the postpulse is also a prepulse at Δt = -3.3ns. This prepulse was measured at an intensity ratio of 4x10^-5.

By synchronizing the round trip times, this prepulse could be shifted in time underneath the intensity pedestal of the main pulse. At the time the postpulse arrives at the injection TFP of the second amplifier, the main pulse is also there. Hence, presuming the intensity of the secondary pulse is lower than the intensity of the main pulse at the time delay of the secondary pulse, the latter could be hidden in the pedestal of the main pulse.

The synchronizing of the round trip times was followed by a commercial Sequoia third-order cross correlator (Amplitude technology). For an additional round-trip time of 2.9ns the first amplifier cavity was extended by 869.398mm.

8080A-16, Session 6

Switching technology for high repetition rate and high energy laser systems

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In high repetition rate and high energy laser systems, optical switches, used for isolating and controlling number of passes, encounter both limitation of aperture and thermo-effects. We describe in detail the design and performance of a reflecting plasma-electrode Pockels cell (RPC) that has thermal properties that make it advantageous for high repetition rate, high energy laser systems (e.g. for laser fusion). The device is a reflective, longitudinally driven, thin-crystal KD*P Pockels cell, constructed with a plasma chamber providing the incident-side electrode and a copper-substrate mirror serving the three purposes of mirror, back-side electrode, and heat sink. The heat sinking role is the most important relative to the scientific advancement being claimed, as it allows the heat generated by laser absorption in the KD*P crystal to be efficiently removed, thereby mitigating thermal birefringence effects that would otherwise degrade the device at high average power. This device, with a 40mm×40mm clear aperture, can be scaled to larger and driven by repetition-rate ~ 12kV voltage pulse. The measured results indicate: the static extinction ratio is greater than or equal to 971:1 locally in the clear aperture, and the dynamic switching efficiency is greater than 99.6%. As far as the shot-to-shot stability of the system concerned, the main jitter comes from the power supply, which is less than 15 ns in 4 hours, corresponding to the jitter of the spark gap in the electrical driver that switches the power to the RPC. The jitter of the gas discharge is greatly smaller than that of the power supply. The simulation results show: For 200 W/cm2 laser power densities, the temperature rise and the transverse temperature difference in the KD*P crystal are respectively 1.65 and 1.27 . The average depolarization in the RPC is 0.13%, and the PV value is 0.24 lamada. These perturbations are acceptable to ensure the laser performance.

8080A-17, Session 6

A new material for single crystal photo-elastic modulators: BBO

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Single crystal photo-elastic modulators (SCPEM) are based on a single piezo-electric crystal which is electrically excited on a resonance frequency such that the resulting resonant oscillation causes a modulated artificial birefringence due to the photo-elastic effect. Polarized light experience in such a crystal a strong modulation of polarization, which, in connection with a polarizer, can be used for Q-switching of lasers with pulse repetition frequencies in the range of 100-1000kHz. Materials for this application should not be optically active and must offer high optical damage threshold, low absorption, low acoustic damping and a piezo-electric effect. A particularly advantageous configuration is offered by crystals from the symmetry class 3m, where a transversal excitation in y-direction is possible, while the light travel along the optical axis (the z-axis), such that no affect on polarization is found in the resting state. The most important eigenmode is then an x-longitudinal oscillation. Besides LiTaO3 and LiNbO3, both already well explored as SCPEM-materials, we introduce now BBO, which offers a very low absorption in the near infrared region and is therefore particularly suited for Q-switching of solid state lasers. In contrast to some early publications, where BBO is assigned to the optically active class 3, it is now clear that it belongs to the class 3m and is therefore suited to be used as a SCPEM. We demonstrate first results of such a BBO-modulator with the dimensions 10x4x4mm in x-, y-, z- direction, which offers a significant resonance and polarization modulation at 130kHz. However, since the piezo-electric effect is rather small, the voltage amplitude for achieving half wave retardation for NIR is in the range of 100V, whereas it is usually <5V for LiTaO3 or LiNbO3. Nevertheless it is a simple and robust device to achieve Q-switching with a high fixed repetition rate for high power solid state lasers.

8080A-18, Session 6

Optical coatings on laser crystals for HiPER project

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In this contribution we present a technology for deposition of interference coatings for optical components designed to operate as active media in power pulsed lasers. The aim of the technology is to prepare crystals for lasers for the HiPER project (High Power laser Energy Research) which should demonstrate the feasibility of laser driven fusion as a future energy source. Diode pumped solid state lasers (DPSSL) are the most likely option for fusion ignition. The choice of material for the lasers active medium is critical. Some of the most important properties include the ability to be antireflection and high reflection coated to reduce the energy losses and increase the overall efficiency. This contribution deals with some of the materials considered to be candidates for slabs serving as the active medium of the DPSSLs. We tested Yb:YAG and Yb:CaF2 samples. As large amounts of heat need to be dissipated during laser operation, cryogenic cooling is necessary. Appropriate coating materials and techniques need to be chosen. Therefore we investigate the differences between available coating techniques in terms of adhesion, enduring of stress resulting from temperature shocks, etc. We designed a special apparatus consisting of a vacuum chamber and a cooling system. The samples were placed into the vacuum chamber which was evacuated and then the samples were cooled down to approximately 120K and illuminated by a pulsed laser. Pulse duration was in the nanosecond region and repetition rate was chosen to be 10Hz as this value is planned to be used in the actual HiPER lasers. Multiple test sites on the samples' surface were used for different laser pulse energies. These experiments also served as preliminary tests of laser damage threshold measurement methodology that we plan to use in the future. We tried to evaluate the laser damage threshold of the material itself as well as of the coatings. Also we used optical and electron microscopy and spectrophotometer measurements for coating investigation after the conducted experiments.

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8080A-19, Session 6

Wide-aperture Faraday isolator for high average power laser system

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In Faraday isolator (FI) for laser systems with a kilowatt-level average power necessary to consider thermal effects (depolarization, thermal lens) induced absorption in magneto-optical elements (MOE). These parasitic thermal effects limit the allowable power in all conventional schemes of FI. In this regard, are urgent tasks to reduce the thermal effects arising in the optical elements.

There are several ways to reduce the thermally induced depolarization: dividing MOE into thin disks cooled by gas; cooling the magnetic system and MOE to cryogenic temperatures; reducing the length of MOE by increasing the magnetic field; find and use alternative materials with better thermo-optical properties and the possibility of manufacturing larger sizes (ceramics,TAG); schemes of FI with compensation of thermally induced birefringence. In addition, the FI used in high-power laser systems require temperature stabilization of MOE. Created on the basis of such schemes of FI are capable of providing reliable isolation at the kilowatt power level of laser radiation.

We theoretically and experimentally investigated schemes of FI with the compensation of depolarization. The optimal parameters for optical elements used in these schemes, for which the value of depolarization ratio is minimum were found. As a result, we developed wide-aperture FI (30mm aperture) based on the TGG crystal cooled by Peltier elements. The effect of compensation of depolarization is observed. At 300W of laser radiation the compensation amounted to 32.8 times. Theoretical estimates show that by using these schemes and the existing crystals we may create a FI with 30dB isolation at laser power of 4kW.

8080A-20, Session 7

Active mirror high energy Yb:YAG amplifier

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Diode-pumped lasers and amplifiers using Yb-doped materials have attracted increasing interest in the past years. This is owed to the high achievable efficiency of high energy amplifiers with high repetition rates and their potential to provide ultrafast laser pulses in the sub 100fs range. These properties allow their use in high intensity physics, laser fusion or pump sources for ultra-short Ti:Sa and OPCPA systems. Yb:YAG is one of the most important material for ns pulse generation and amplification with high efficiency also at room temperature. Here we present a joule-class Yb:YAG active mirror amplifier and the time-resolved analysis of its thermal lens. The active mirror concept is one of the most promising techniques for room temperature operation of Yb-based lasers providing efficient cooling of the laser material and energy extraction. A pulse energy of 730mJ at a repetition rate of 1Hz was obtained at an optical-to-optical conversion efficiency of 16%. Here a relay-imaging multipass cavity with 4 extraction passes and also 4 pump passes was employed. For seeding a Yb:YAG pre-amplifier with a output energy of 65mJ was used. The disk with an Yb-concentration of 5mol% comprises a thickness 2.5mm and diameter of 12.5mm. At pump energies of 4J and above the small-signal gain was drastically reduced by transverse lasing which was observed as a roll-over of the measured gain and efficiency. In order to get rid of parasitic lasing the doping concentration will be reduced while the thickness is increased such that the optical thickness of the disk remains. Furthermore, a multiple active mirror will be used in a redesigned setup allowing reduced thermal load of each single disk. The thermal lens measurements were compared with a rod type (transversally) cooled disk. At a repetition rate of 10Hz the thermal equilibrium of the disk was attained within the first pump shots while in the case of the rod type cooling serveral seconds were required.

8080A-21, Session 7

Joule-level, diode-pumped, room-temperature Yb:CaF2 amplifiers

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The Research Centre Dresden-Rossendorf is planning to build a fully diode-pumped Petawatt laser based on Ytterbium-doped calcium fluoride. A pulse energy of 200J, a repetition rate of 1Hz and a pulse duration of 200fs after compression are desired. In this project a total pump peak-power of 1.5MW is scheduled assuming a pump pulse duration of 2ms and a targeted optical-to-optical conversion efficiency of 10%. Here we present gain measurements and time-resolved analysis of the thermal lens of different Yb:CaF2 amplifier configurations. The active mirror concept is one of the most promising techniques for room temperature operation of Yb-based lasers providing efficient cooling of the laser material and energy extraction. Therefore, a disk amplifier was compared with a rod laser. A pulse energy of 600mJ at a repetition rate of 1Hz was achieved using a cylindrical rod with a length of 20mm, a diameter of 28mm and an Yb-concentration of 2mol%. For seeding an Yb:YAG pre-amplifier produced pulses with a duration of 6ns. With a 2-disk Yb:CaF2 amplifier comprising of 8 extracting beams and a pump recovery configuration the minimum required pump fluence in order to bleach out re-absorption at the laser wavelength of 1030nm was reduced roughly by a factor of two down to 13J/cm2. Furthermore, the thermal lens power was reduced from 5dpt of the rod down to smaller than 0.05dpt for 3mm thin disks at 10Hz.

8080A-22, Session 7

Analysis of thermo-optic effects in Nd:YAG ceramics disk under high heat load

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The main obstacles in development of high energy and high power lasers are thermal effects occurring under high heat load, high intensity pumping. The special geometries of pumping e.g. heat capacity laser, double-clad fiber, thin disk approach mitigate such effects to certain extent. However, despite low quantum defect (typical for Yb doped media) and very sophisticated method of cooling, the longitudinal and transverse temperature gradients occur almost in every case for CW high heat load pumping and therefore restrict the available power and energy. The aims of work were theoretical analysis of thermo-optic effects occurring inside disk shape ceramic gain elements and its experimental verification. For theoretical analysis we have applied the semi-analytical model based on thermo-elasticity theory and compared it to results obtained applying COMSOL Multiphysics software. Thermally induced distortions, thermally induced stresses and birefringence were calculated for several gain elements of rod, disk and slab shapes. The special attention was paid to disk shape gain elements, that are ones of promising geometries for high energy amplifiers. The special elements made of Nd:YAG ceramics of 15-mm diameter and 3-mm thickness were prepared for experimental verification of the theoretical models. In preliminary experiments, we achieved near 5 mJ for 16 mJ of absorbed pump energy corresponding to about 34% of slope efficiency. To characterize the spatial inhomogeneities of output parameters we have implemented the “half-microchip configuration” with output coupler formed by uncoated output facet of plane parallel ceramic sample of disk shape and separate, flat, rear mirror. About 5% of r.m.s. variance of output energy distribution were achieved in the best case. The special laboratory set-up enabling simultaneous registration of thermally induced birefringence and wavefront distortions was worked out. The conoscopic images were recorded in far field enabling the analysis of thermally induced birefringence. Simultaneously, the probe beam reflected back at both sample facets (forming a Fizeau interferometer) enabling the analysis of the thermo-optically induced wavefront aberrations. We have investigated the thermo-optics effects for different heat densities in range of 0.1 kW/cm2 up to 5 kW/cm2 changing the duty cycle of pump power. The experiments were carried out in lasing and non lasing conditions. The heat conversion efficiency for given Nd:YAG ceramics sample and maximum pump

density corresponding to acceptable level of thermal distortion were determined.

8080A-23, Session 7

Comprehensive simulation of an edge pumped composite Yb:YAG/YAG asymmetric hexagonal disk laser

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Thin disk lasers or active media configurations have recently been demonstrated at cw output powers exceeding 1 kW with the promise of very high beam quality. Today, the dominant development of this type of laser is being pursued at the Stuttgart University. In the end-pumped approach of thin disk laser, by using a parabolic mirror and several reflective prisms, the pump beam is re-imaged through the gain media up to 32 times. The important disadvantage of this approach is its complicated pump geometry and transversal growing of amplified spontaneous emissions (ASE). If an index matched undoped cap is added on the Yb:YAG layer, associated problems of the multipass approach are solved. Firstly, It enables side pumping of the thin disk by guiding the pump light. Without YAG layer, the transversal photons has longer path to amplification but with added YAG cap, ASE as well as parasitics is suppressed by more than 10x. Finally, it helps to reduction of temperature through thermal diffusion at Yb:YAG and YAG boundary.

In this article we present and design a new structure of a composite Yb:YAG/YAG asymmetric hexagonal thin disk laser (CAHTDL). CAHTDL consists of a thin disk gain crystal with thickness td that has on top a diffusion bounded material with thickness tu. The hexagonal disk and index matched layer, both have 30 degree canted facets at their edges. It should be noticed that the pump light input window and its opposite face have parallel cutting directions whereas this direction is non-parallel for the two neighbor faces. The pump beam is delivered through three lens ducts and impinges onto input window by angle - with respect to the horizontal line and propagates inside the undoped cap and gain crystal through total internal reflections (TIR). Three pump windows spaced at 120 degree each one 30 degree with respect to the optical axis were cut on the undoped YAG cap. The bottom surface of the Yb:YAG crystal has HR coatings at the lasing and pumping wavelengths. It should be noticed that the opposite facets of the pumping windows and the top face of the undoped material don't have any HR coatings at the pumping wavelength and the pump light propagates along a zigzag path via this surfaces through TIR, so this configuration allows the multi-pass of the pump beam using only composite gain media structure. Finally the bottom layer of the composite thin disk is indium soldered to a high performance cooler, so heat is extracted through the thin film coatings during lasing. The three diodes are placed outside the asymmetric hexagonal shape disk, and the emitting light is coupled to the three lens ducts.

At the first step of modeling, the absorbed pump distribution is calculated by Monte Carlo ray tracing method; secondly with using the fraction of the absorbed pump density as the heat source, the temperature distribution is simulated by 3D-FEM. Finally the output power is calculated by solving the quasi-three-level system rate equations. The absorption efficiency, the pump uniformity and the temperature distribution are three effective parameters on the laser system operation. These parameters are investigated and optimized by this model. Our simulation results shows this edge-pumped geometry of disk laser has scaling potential of solid state lasers to kW ranges.

8080A-24, Session 7

Simulation and optimizing of quasi longitudinal pumped Yb:YAG thin disc laser operation

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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. To the our knowledge, so far our model is the only model which have applied more dependences in the numerical calculation of the disc laser, so its simulated 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 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 centigrade degree 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.

8080A-29, Session 7

LUCIA advanced cryogenic amplifier

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A major challenge the HiPER project is facing is to derive laser architectures satisfying simultaneously all HiPER requirements; among them, high wall-plug efficiency (15 to 20%) and repetition rate (5 to

10 Hz) are the most challenging constraints, being indeed, until now, never taken into consideration while designing a several hundred kJ laser system.

We will describe two laser options based on Yb:YAG and one on Yb:CaF2. All options rely on Helium gas for cooling. While high pressure flow of Helium will be required to cool multislabs based amplifiers designs, sub-atmospheric pressure static cell is proposed for active mirror based amplifiers.

8080A-25, Poster Session

Thermo-optical effects on quasi-cavity performance used for end-pumped thin-disk solid state lasers

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Minimal thermal lensing are the particular features of the thin - disk solid - state laser (TDSSL).One of the most important problems concerned with the pumping geometry of a laser crystal is how to shape a diverging beam and transfer it into the laser crystal. The absorption efficiency of a quasi-end pumped thin-disk laser (TDL) is very low because of its small thickness. Therefore, the unabsorbed pump light must be re-imaged onto the disk several times. For this purpose, a novel pump design for pumping the TDL was presented by Giesen and co-workers in 1999 and more recently, Bourdet and co-workers [1, 2]. Dependence of the pump spot size on the injected pump divergence and distance between mirrors and active medium due to the disk deformation effects are developed [3]. In addition, the dependence of the pumping efficiency on the length of the quasi-cavity and the divergence of the injected pump beam have been investigated [4].

In selection of the quasi-cavity material, thermal and opto - mechanical properties were of interests. Material for quasi-cavity can be glass and crystalline medium. It can be useful for CW high powers or high duty -cycle pulsed pumping by define an appropriate reflectivity of end planes and thermal analysis of quasi-cavity which reduce high intensity damages inside the quasi-cavity.

Based on their investigation, we report the predicted thermo-optical behavior in circular and square section of quasi-cavity by using analytical and numerical finite element analysis (FEA) methods. Then, we present the heat load, temperature distribution, stress and displacement components of quasi-cavity which are resulted in pump light distribution profile and temperature gradient inside the crystal. Our results demonstrate the thermal effects due to the pump light power density in cubic and square section of quasi-cavity are more uniform than in circular - shape. Finally, we recommend a combination of diamond / YAG crystal in quasi-cavity construction for better performance in high power end-pumped thin - disk laser.

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8080A-26, Poster Session

Exploration of selective excitation of Mathieu-Gauss modes in end-pumped solid state lasers

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Nondiffraction beams has been attracted since Durnin et al. first discover the generation of Bessel beams in 1987 [J. Opt. Soc. Am. A 4, 651]. Particularly, the Helmholtz-Gauss beams are kind of nearly nondiffraction beams which carry a finite power and can be realized experimentally to a very good approximation [J. Opt. Soc. Am. A 22, 289]. Mathieu-Gauss beams (MGBs) are one kind of Helmholtz-Gauss beams that are solutions of wave equation in elliptic coordinate, which are recently been observed directly in a real laser system [OPTICS EXPRESS 16, 18770]. This study drafts simulation code to model the optical filed oscillation of end-pumped solid-state lasers. We proposed a new kind of axicon-based stable laser resonator, and find a systematic method to the selective excitation of Mathieu-Gauss beams in end-pumped solid-state lasers with the proposed resonator. In this study, Mathieu-Gauss beams are classified into to two categories ($q=0$ MGBs and $q>0$ MGBs) by its ellipticity parameter q. By using the proposed resonator, the selective excitation of $q=0$ MGBs and $q>0$ MGBs can be easily achieved by azimuthally pumping scheme. With the proposed approach, we can selectively excite Mathieu-Gauss beams in end-pumped solid-state lasers with a specified order. Other possible way to the selectively excitation of Mathieu-Gauss beams in the proposed axicon-based stable laser resonator are also discussed in this study. The achieving of selectively excitation of Mathieu-Gauss beams would be helpful to several researches which might adopt Mathieu-Gauss modes, such as localized X-waves [J. Opt. Soc. Am. A 21], photonic lattices [Opt. Lett. 31, 238], and the transfer of angular momentum [Opt. Express 14, 4182] and etc.

8080A-27, Poster Session

Suppression of ASE using the co-doping technology

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The self-Q-switch laser pulse can be achieved in appropriately co-doped Cr^{4+} in Yb:YAG crystal due to the saturable absorption characteristic of the Cr^{4+} ion. The laser dynamical model, including the Amplified Spontaneous Emission(ASE) effect, was established based on the rate equation for the Cr^{4+},Yb:YAG crystal. The amplifier, using the Cr^{4+},Yb:YAG crystal, was simulated for different doped density of Cr^{4+} and Yb^{3+}. And a lot of significative results ware got. The results indicated that: the co-doped Cr^{4+} in crystal Yb:YAG only absorb the pumping energy and decrease the energy storage, when ASE is low(small aperture and low density of Yb^{3+}). In contract, when the ASE in amplifier is significant(large aperture and high density of Yb^{3+}), the co-doped Cr^{4+} ion will seriously affect the energy storage, with the increasing of density of co-doped Cr^{4+} in crystal, the energy storage increase firstly, and then decrease after a maximum value. The energy storage in amplifier with co-doped 0.06at% Cr^{4+} ion in Yb:YAG crystal will increase 10% in comparison with the Yb:YAG, when the pumping aperture was 15mm×15mm, thickness was 1.5mm, and the Yb^{3+} ion density was 10at%.

8080A-28, Poster Session

A ridge waveguide quantum well ALGAAS/ GAAS laser design

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The aim of our study was three folds: (1) to provide the comprehensive analysis and calculations to design a ridge waveguide laser. In the simulations, the thicknesses of SCH layers, inner cladding layers and outer cladding layers are varied in order to observe variations of far-field divergence and the total confinement factor as functions of layer thicknesses. Comparison among loss, narrow far-field divergence and high confinement factor are made to optimize layer thicknesses,

(2) The thickness of an etch stop layer is optimized to achieve the required lateral effective refractive index difference, and also the far-field divergence of the ridge waveguide laser, (3) the channel width and ridge width are designed to maintain single lateral mode and low loss by using the three layer dielectric slab waveguide calculations. The details of simulation using WAVEGUIDE software are provided in the following figures. Also there is a summary of the designed laser:

Confinement factor (Γ): 0.01297672 , far field Divergence angle (θ) : 26 degrees.

It is believed that our study might provide an accurate analytical approach to design ridge waveguide lasers. The width of the ridge region is obtained by calculation for single-lateral-mode operation and we have 3.47 micrometers for it which only TE0 mode can propagate which satisfies the minimum requirement for a perfect laser. The present results are also useful for the design of other equivalent lasers.

Conference 8080B: ELI: Ultrarelativistic Laser-Matter Interactions and Petawatt Photonics

Monday-Wednesday 18-20 April 2011

Part of Proceedings of SPIE Vol. 8080B ELI: Ultrarelativistic Laser-Matter Interactions and Petawatt Photonics

8080B-30, Session 10

MEGa-rays, petawatts and nuclear photonics

C. P. J. Barty, Lawrence Livermore National Lab. (United States)

No abstract available

8080B-31, Session 10

Extreme Light Infrastructure: nuclear physics

V. Zamfir, F. Negoita, Horia Hulubei National Institute of Physics and Nuclear Engineering (Romania); D. Habs, Ludwig-Maximilians-Univ. München (Germany)

Spectacular progress of electron and heavy-ions acceleration driven by ultra-short high-power laser has opened the way for new methods of investigations in nuclear physics and related fields. On the other hand, by upshifting the photon energies of a high repetition TW-class laser through inverse Compton scattering on electron bunches classically accelerated, a high-flux narrow bandwidth gamma beam can be produced. With such a gamma beam in the 1-20 MeV energy range and a two-arms multi-PW class laser system, the pillar of “Extreme Light Infrastructure” to be built in Bucharest will focus on nuclear phenomena and their practical applications. Nuclear structure, nuclear astrophysics, fundamental QED aspects as well as applications in material and life sciences, radioactive waste management and homeland security will be studied using the high-power laser, the gamma beams or combining the two.

The presentation will include the general description of ELI-Nuclear Physics (ELI-NP) facility, an overview of the Physics Case and details of the most representative proposed experiments.

8080B-32, Session 10

Scaling the technology of the Texas petawatt laser to exawatt peak powers

T. Ditmire, The Univ. of Texas at Austin (United States)

No abstract available

8080B-33, Session 11

Progress at the multi-PW ELI-NP laser facility in Romania

D. Ursescu, National Institute for Lasers, Plasma and Radiation Physics (Romania)

No abstract available

8080B-34, Session 11

TBA (ELI CZ)

B. Rus, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

No abstract available

8080B-35, Session 11

Present status and recent developments on the APOLLON 10PW French laser

J. Chambaret, Ecole Nationale Supérieure de Techniques Avancées (France)

No abstract available

8080B-36, Session 12

LASERIX: an open facility for developments of Soft X-ray and EUV lasers and applications

D. R. Ros, Univ. Paris-Sud 11 (France)

LASERIX is a high-power laser facility designed to produce High-repetition-rate XUV laser beams pumped by a Titanium:Sapphire la-ser. The objectives are to develop soft X-ray lasers (SXRL) at various wa-velengths and use them for applications. The facility is based on a tita-nium-doped sapphire (Ti:Sa), delivering pulse energy of 2 J at 10 Hz repetition rate at the exit of the front-end and 40 J before compression at 0.1 Hz repetition rate (using a Ti:Sa crystal amplifier of 10 cm in diame-ter).

The large width of the Ti:Sa spectrum opens the way to short pulses and to new SXRL schemes. Thus, LASERIX will provide the opportunity to study a large variety of SXRL schemes beside the conventional “transient collisional” one (OFI pumping, inner shell X-ray lasers, ...).

The 40-J beam will be basically divided in two parts that can be indepen-dently compressed, resulting in two beams of 10 J with a pulse duration which is continuously tunable between 40 fs and 500 ps. Three different EUV and soft x-ray beam lines will run simultaneously: An EUV DGRIP/GRIP laser line at 10Hz, a femtosecond EUV high order harmonic laser line at 10Hz and a high energy soft x-ray laser line at 0.1Hz.

This configuration highly enhances the scientific opportunities of the facil-ity. Indeed it will be possible to perform both Soft X-ray laser experiments and more generally pump/probe experiments, mixing IR and EUV sources. Then, this facility will be useful for the community, opening a large scale of Laser Interaction with Matter investigations.

In this contribution, the main results concerning both the perspectives of the development of EUV and soft x-ray laser sources and their use for scientifical applications will be presented.

Finally, we will indicate the perspectives of the LASERIX facility in the near future, especially taking into account the national (Institut de la Lu-mière Extrême: ILE project, laboratories working on the development of the XUV sources) and international (Extreme Light Infrastructure project) contexts.

8080B-37, Session 12

Large aperture Nd:glass amplifiers with high-pulse repetition rate

A. A. Kuzmin, A. A. Shaykin, E. A. Khazanov, Institute of Applied Physics (Russian Federation)

Recently an interest in nanosecond Nd:glass lasers has increased all over the world. Such lasers are widely used for experiments on laser thermonuclear synthesis and in other fundamental and applied researches. One of the examples is ELI. Nd:glass is indispensable for creation of powerful femtosecond laser setups of petawatt level. In all types of petawatt lasers and projects energy is initially reserved in

a nanosecond pulse of Nd:glass laser. Limitations on pulse repetition rate are thermal effects in Nd:glass caused by low heat conductivity and large aperture of glass amplifiers. A basic restriction is glass fracture when the thermally induced pressure threshold is exceeded. In practice, however, lasers work with smaller repetition rates because of accumulation of radiation depolarization and strong aberrational thermal lens. All these effects reduce the quality of laser radiation.

The results of studies of thermally induced depolarization and thermal lens in large aperture Nd:glass rod amplifiers (100, 85, 60 and 45 mm in diameter) are reported in this paper. These amplifiers are used in a petawatt parametrical laser system PEARL (IAP RAS, Nizhny Novgorod, Russia). Our investigation will allow us significantly decrease the pulse repetition period from 30 to 3 minutes.

Also it is shown the possibility of creation of a 200 J 20 ns Nd:glass laser with a pulse repetition period about a minute. The radiation of this laser can be used as a pump for a Ti:Sa crystal. It allows generating sub-petawatt pulses with high repetition rate.

8080B-38, Session 12

Study of acousto-optic programmable dispersive filter for amplitude and phase control of femtosecond seed pulse in sub PW OPCPA laser system

V. Ginzburg, E. Katin, E. Khazanov, V. Lozhkarev, M. Martyanov, I. Yakovlev, Institute of Applied Physics (Russian Federation); S. Chizhikov, V. Molchanov, N. Solodovnikov, Moscow State Institute of Steel and Alloys Technological Univ. (Russian Federation); Y. Kitaev, Voronezh State Univ. (Russian Federation)

The quality of compressed pulse in high peak power laser systems based on chirped pulse amplification is determined by non compensated high order dispersion and gain bandwidth narrowing in amplifiers. Programmable device modifying spectral amplitude and phase of seed femtosecond pulse can be used for improving duration and contrast of compressed pulse and increasing amplification efficiency.

Proposed by P. Tournois acousto-optic programmable dispersive filter (AOPDF) seems to be the most suitable for this purpose. The AOPDF is based on collinear acousto-optic interaction. During this interaction each spectral component of femtosecond pulse diffracted in mode with different group velocity with efficiency and position determined by acoustic wave amplitude and frequency. So, the control of acoustic wave provides modification in spectral phase and amplitude.

We designed and implemented an original AOPDF and tested it in front-end system of sub PW laser based on optical parametrical chirped pulse amplification (OPCPA). The front-end system was based on one double-pass optical parametric amplifier (OPA) made from KD*P crystal. The femtosecond master oscillator was a Cr:forsterite laser generating 40 fs pulses at a central wavelength of 1250nm. The stretcher expanded the pulse duration up to 600ps. The OPA were pumped by the second harmonic of Nd:YLF laser with a wavelength of 527 nm. During the first pass, the OPA performed broadband conversion of chirped pulses at 1250 nm into pulses of signal radiation at 910 nm. During the second pass, the 910 nm radiation was amplified. After OPA part the signal radiation derived to spectrograph for diagnostic. The amplified chirped signal pulse was compressed in a standard grating compressor. Single-short autocorrelator was used for measurements of compressed pulse parameters.

AOPDF cell was placed between femtosecond oscillator and stretcher. The diffracted output beam has no deflection from initial direction, this fact allowed to implement AOPDF in existing lasers easily. The filter operates with central wavelength of 1250 nm with bandwidth of 120nm. Maximal programmable delay was 15 ps. Usage of acousto-optic paratellurite single crystal with length of 53 mm allows reaching diffraction efficiency of 70%. In the case when the AOPDF was tuned to transform the whole spectrum of femtosecond pulses, measured signal spectrum was equal to signal spectrum without AODF. Also the AOPDF has demonstrated high spectral resolution (~1 nm) and acceptable contrast (not worse than 1:100). Shaping of sound amplitude distribution providing gaussian gap in transforming function produced corresponding modifications in signal spectrum. Proper selection of gap's depth and width values provided enlarging signal spectrum bandwidth in twice. Applying of additional second and third order dispersion to the phase of injected femtosecond pulse provided corresponding changes in the measured autocorrelation function of compressed signal pulse. Those changes were in good agreement with results of numerical simulation.

AOPDF cell demonstrated high efficiency, flexibility of seed pulse control and simplicity of operation. It opens way for achievement signal radiation with power more than 1 PW by increasing of parametric efficiency and shortening pulse duration dew to compensation of stretcher-compressor dispersion.

8080B-39, Session 12

Secondary sources of ELI-PP

N. C. Lopes, Univ. Técnica de Lisboa (Portugal)

No abstract available

8080B-40, Session 12

Progress of the ELI attosecond facility project in Hungary

and novel schemes for attosecond pulse generation

P. Dombi, Research Institute for Solid State Physics and Optics (Hungary)

No abstract available

8080B-41, Session 13

Generation of giant attosecond pulses at the plasma surfase in the regime or relativistic electronic spring

A. M. Sergeev, Institute of Applied Physics (Russian Federation)

No abstract available

8080B-42, Session 13

Perspectives for a laser-driven XFEL

F. J. Grüner, Ludwig-Maximilians-Univ. München (Germany)

No abstract available

8080B-43, Session 13

Modelling and design of high harmonic seeding in soft x-ray laser plasmas with both direct and stretched amplification techniques: application to ELI facilities

P. Zeitoun, Ecole Nationale Supérieure de Techniques Avancées (France) and ENSTA-ParisTech (France) and ecole Polytechnique-ParisTech (France); E. Oliva, Ecole Polytechnique (France); M. Fajardo, Univ. Técnica de Lisboa (Portugal); P. Velarde, Univ. Politécnica de Madrid (Spain); D. Ros, Univ. Paris-Sud 11 (France); S. Sebban, Ecole Nationale Supérieure de Techniques Avancées (France)

Process of seeding a soft x-ray laser by high harmonic beam demonstrated outstanding optical qualities like near gaussian cross-

section, full transverse coherence, tunable polarization, diffraction-limited wave front [1]. However, despite several attempts worldwide seeded soft x-ray lasers never succeeded in reaching energy per pulse higher than 1 µJ and even 90 nJ for solid amplifiers [2]. Surprisingly, the highest energy worldwide has been experimentally achieved with gas amplifier that is known to store less energy than solid amplifier. Based on 2D hydrodynamic modelling and 3D ray-trace modelling we demonstrated that adequate plasma tailoring opens up the way to achieve up to 20 - 40 µJ per pulse [3].

In Amplification of Spontaneous Emission (ASE) mode, x-ray lasers pumped by long (400 ps) laser pulse demonstrated energy up to 12 mJ per single pulse, but with very weak coherence and no polarisation [4]. Seeding such high-energy amplifier represents a very promising challenge however the only related experiment [5] was not so successful. Our numerical investigation using Bloch-Maxwell model shown that direct seeding of such high-energy, long live amplifier cannot extract more than 100 µJ, in 200 fs pulse. Therefore, we proposed and extensively studied the seeding of stretched high harmonic pulse so as to fit the gain duration. In that case, the total stored energy (12 mJ) can be extracted and further compress down to 200 fs.

Scaling of stretched seed amplification shown that the system is beneficial from small system (pump laser with few Joules) up to very large system like ELI. We performed the full design of such soft x-ray amplification chain to be implemented on ELI, completed by a possible timetable showing that seeded soft x-ray laser may deliver photons to users within few years followed by strong intensity raise with years culminating around 1019 Wcm-2.

References :

1- Ph. Zeitoun et al, Nature, 431, 426 (2004)

2- Wang et al, Phys. Rev. Lett., 97, 123901 (2006)

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4-B. Rus et al, Phys. Rev. A, 66, 063806 (2002)

5- T. Ditmire et al, Phys. Rev. A, 51, 6 (1995)

8080B-44, Session 14

Radiation pressure acceleration of ions in the ultraintense regime

M. Borghesi, Queen's Univ. Belfast (United Kingdom)

No abstract available

8080B-45, Session 14

Latest progress in electron acceleration and laser development at MPQ

S. Karsch, Max-Planck-Institut für Quantenoptik (Germany)

No abstract available

8080B-46, Session 14

Multiple beams for laser wakefield driven particle acceleration

V. B. Pathak, J. M. Vieira, R. A. Fonseca, L. O. Silva, Univ. Técnica de Lisboa/Instituto Superior Técnico (Portugal)

Laser driven wakefield acceleration (LWFA) holds the promise of reaching the energy frontiers where it will require ultra high-intense lasers; and this is a main goal for future laser systems like ELI. Recent simulations1 for LWFA have shown that lasers with energy around 300J are required to achieve mono-energetic electrons with tens of GeV energy. One of the ways to achieve such high powers is to mix multiple laser beams, a technique already in use or that will be used for the present and future laser driven fusion experiments (e.g. NIF and HiPER). Since separate optical units are involved in the amplification of each laser beam, chances of getting each pulse with different phase, frequency and field profile are very high. These laser pulses with distinct characteristics, when collimated to get final high power pulse, introduce asymmetry and modulation in the envelope and enhancement in the bandwidth of final pulse. We discuss here the effect of frequency mismatch over the multiple beams on wakefield excitation and final accelerated beam parameters such as maximum energy, energy bandwidth, bunch length, etc. A theoretical model developed for the linear regime shows that the wakefield amplitude scales with the inverse of the frequency bandwidth, provided the envelope of the laser is symmetric and smooth, which is valid for the frequency mismatch up to 5% of the central frequency for 10 lasers beams. Since the nature of frequency mismatch is random, adding more beams provides smoother and symmetrical profiles. Depending upon the envelope asymmetry in the laser, this can enhance or reduce the wakefield amplitude. In the nonlinear regime, our results indicate that the variation in laser bandwidth has a strong effect on the injection time and total charge in the accelerated electron beam. For the final pulse obtained by collimating 10 lasers with frequency mismatch up to 2% of the central frequency, maximum energy, total charge and bunch length of the accelerated electron beam are of the same level and do not suffer significant reduction. For higher mismatch, significant reduction in the beam quality in terms of energy, charge and size is observed. Our studies show strong dependence of accelerated beam quality on frequency mismatch. For given number of laser beams there exist a threshold frequency mismatch beyond which the accelerated electron bunch quality is very poor, and increasing the number of laser beams can increase this threshold.

Reference:

1. S. F. Martins, R. A. Fonseca, W. Lu, W. B. Mori, and L. O. Silva, Exploring the future of laser wakefield acceleration using particle-in-cell simulations in Lorentz boosted frames, Nature Physics, 6, 311 (2010)

8080B-47, Session 14

Petawatt peak power photons for monoenergetic beams of gigavolt energy electrons and megavolt energy x-rays

D. P. Umstadter, Univ. of Nebraska-Lincoln (United States)

No abstract available

8080B-48, Session 14

A scalable, performant, highly-parallel particle-in-cell code for fast simulations of large laser-plasma experiments

M. H. Bussmann, H. Burau, F. Berninger, A. Debus, A. Irman, A. Jochmann, Forschungszentrum Dresden-Rossendorf e.V. (Germany); W. Hönig, F. Schmitt, R. Widera, G. Juckeland, W. Nagel, Technische Univ. Dresden (Germany); U. Schramm, T. E. Cowan, Forschungszentrum Dresden-Rossendorf e.V. (Germany)

A scalable, performant, highly-parallel Particle-in-Cell code for fast simulations of large Laser-Plasma experiments. Investigating parameters for optimizing laser particle acceleration is a time-consuming task since realistic simulations of laser plasma interactions using the particle-in-cell technique can require the computation of several hundred million particle trajectories on a grid of several ten million cells.

The computational effort needed to investigate the dependence of the performance of new acceleration scenarios on only a few parameters thus normally requires the use of large-scale high-performance computing systems only available at central super computing centres. Thus, parameter scans are usually performed by reducing the system size, the particle density, the computation time and the dimensionality of the problem. Such a scan is then at best complimented by a small number of more realistic large-scale simulations with parameters closer to the experimental parameters.

Recently, general purpose graphical processing units (GPGPUs) have

entered the stage of high performance computing. This new hardware offers a computational power exceeding that of standard CPU-based computers by several orders of magnitude at much lower investment and maintenance costs. Making good use of this computational power is only possible if the algorithm can run on a massively parallel system consisting of a huge number of independently working processors. However, the memory on a single GPGPU and thus the system size that can be computed on it is limited

We present PIConGPU [1], a particle-in-cell algorithm that can run efficiently on a cluster of GPGPU nodes. PIConGPU can run large-scale, realistic simulations by mapping the physical system onto many GPGPUs. Thus, the time needed to calculate the evolution of the large system is comparable to the time it takes to compute the small sub-region that can fit on a single GPU and therefore can lead to turnaround times of only a few hours for a hundred thousand time steps and single time steps of under a nanosecond per macro-particle [2].

If computational stability and dispersion is treated appropriately, using GPGPUs to simulate for example laser wakefield acceleration of electrons can greatly enhance the study of large parameter spaces while at the same time using simulation parameters resembling those of the experimental system studied.

We focus on real-world examples of using PIConGPU for the simulation of laser electron acceleration scenarios investigated with the DRACO laser system at the Forschungszentrum Dresden-Rossendorf and show how the fast response time of GPGPU-based simulations can open up the path for optimizing experimental parameters.

[1] H Burau, et al, PIConGPU : A Fully Relativistic Particle-in-Cell Code for a GPU Cluster, IEEE Transactions on Plasma Science 38(10), 2831-2839 (October 2010)

[2] W. Hönig et al, A Generic Approach for Developing Highly Scalable Particle-Mesh Codes for GPUs, SAAHPC 2010 extended abstract

8080B-50, Session 15

High intensity laser plasma interactions in the context of fusion fast ignition

V. Tikhonchuk, Univ. Bordeaux 1 (France)

No abstract available

8080B-51, Session 15

Probing new physics using high-intensity laser systems

M. Marklund, Umeå Univ. (Sweden)

No abstract available

8080B-57, Session 15

High-energy quantum dynamics in ultra-strong laser pulses

C. H. Keitel, Max-Planck-Institut für Kernphysik (Germany)

No abstract available

8080B-52, Session 16

Simulation of radiation back-reaction into the QED regime

N. Naumova, Ecole Polytechnique (France)

No abstract available

8080B-53, Session 16

Electron-positron-photon cascades in strong laser field

M. Legkov, A. M. Fedotov, National Research Nuclear Univ. MEPhI (Russian Federation)

The highest intensity of laser radiation available for experimentalists is at present about 10^(22) W/cm^2. However, in the nearest future the ambitious ELI project may provide its boost up to 10^(24)-10^(26) W/cm^2. Such unprecedentedly high intensity level may open possibilities to explore a new regime of laser-matter interactions with domination of QED processes.

Different sorts of QED predictions may become accessible for observations. In our mind, the most important among them is production of QED cascades. Namely, even subcritical laser field is able to accelerate the initially slow seed electrons to ultrarelativistic energies from hundreds MeVs to tens GeVs. In a certain scenario, such electrons emit multiple hard photons, which in turn can produce in the field electron-positron pairs. The newly created electrons and positrons also accelerate radiating hard photons and so on. Using a model of two colliding counter-propagating laser beams it was shown that the number of particles during the process is growing exponentially in time. This leads to vast formation of electron-positron-photon plasma in the region of overlap of the beams. According to numerical simulations, this plasma quickly absorbs an essential part of the energy of the laser field thus leading to its depletion. We have stated before that this process imposes natural limits for both the cascade development and the maximal attainable intensity of the laser field.

Our talk will consist of two parts. In the first part we will review the previous goals of our group in studies of cascade production in the laser field. In particular, we plan to discuss the origin of the cascades, the qualitative theory and review the recently published numerical simulations. In the second part we will discuss further improvements of our model for cascade production. These recent developments are mostly related to taking into account such lower-order inverse (recombination) processes as photon absorption and one-photon annihilation.

8080B-54, Session 16

Full-scale modeling of fast ignition with ultra-intense lasers

F. Fiuza, M. Marti, R. Fonseca, L. Silva, Univ. Técnica de Lisboa (Portugal); J. Tonge, J. May, W. Mori, Univ. of California, Los Angeles (United States)

The next generation of laser systems promises tremendous developments in laser-plasma interaction experiments. In fast ignition of fusion targets, near-future more powerful lasers will reach the conditions required for ignition at ultrahigh intensities. Numerical simulations play a crucial role in understanding the physics and optimizing the physical parameters and setup of these upscale experiments. However, the different spatial and temporal scales involved make these numerical experiments extremely demanding in terms of computational resources and multi-dimensional full-scale simulations are not yet possible to accomplish.

Following the work on a optimized hybrid algorithm for modeling inhomogeneous plasmas by B. Cohen et al. [J. Comp. Phys. 229, 4591 (2010)] an hybrid algorithm was implemented in OSIRIS 2.0 [R. A. Fonseca et al, LNCS 2329, III-324 (Springer-Verlag, 2002)]. This novel framework merges accurate collisional PIC models between regions where only the field solver is reduced in the collisional region, allowing for the self-consistent modeling of all the relevant physics at different scales, and leading to a dramatic change in the computational resources required to model fast ignition.

We will demonstrate how OSIRIS can be used to perform for the first time full-scale simulations of fast ignition with ultrahigh intensity lasers, where the critical issues of laser absorption, electron transport in the collisional plasma, and energy deposition in the very dense core will be addressed in a fully self-consistent manner. Our results, for different laser intensities and target configurations, provide an integrated physical picture of the overall interaction and clear directions for the

realization of fast ignition as an efficient scheme for inertial fusion energy.

8080B-55, Session 16

Radiation cooling dominated regimes in particle-in-cell simulations

M. Vranic, Univ. Técnica de Lisboa (Portugal); J. L. Martins, S. F. Martins, Instituto Superior Tecnico (Portugal); R. A. Fonseca, Instituto Superior Tecnico (Portugal) and Univ. Técnica de Lisboa (Portugal); L. O. Silva, Instituto Superior Tecnico (Portugal)

Under extreme acceleration, charged particles can radiate strongly and the corresponding radiation damping/cooling can become important in the plasma energetics and dynamics in astrophysical and laboratory scenarios. This occurs when the radiated energy in a typical oscillation period (e.g. cyclotron period or laser period) is comparable to mc2. In particular, under the presence of ultra high static fields or high intensity lasers, the motion of particles in the ultrarelativistic regime can be severely affected by radiation damping. The standard particle-in-cell (PIC) algorithms cannot capture radiation damping effects for the range of frequencies radiated by relativistic electrons. We have compared relevance/advantages of several models for the calculation of the radiation damping force and developed a radiation cooling algorithm for Osiris [1]. Using a single particle dynamics code and Osiris 2.0 framework, we have examined and identified different qualitative regimes for electron interaction with counter- and co- propagating ultra-intense laser fields. For conditions where the radiation cooling is important, qualitative differences arise as compared with the scenarios where radiation cooling is absent; this is reflected not only in the particle phase space trajectories, but also on the net velocity imparted to the counter-propagating electrons, and the possibility of cooling particle beams.

References

[1] R. A. Fonseca et al. OSIRIS: A three-dimensional, fully relativistic particle in cell code for modeling plasma based accelerators. Lect Notes Comput Sc (2002) vol. 2331 pp. 342-351

Work partially supported by FCT (Portugal).

8080B-56, Session 16

Vision of positron science with ELI Beamlines

L. Drska, Czech Technical Univ. in Prague (Czech Republic)

The dawn of the delivery phase of the project ELI prompts to think intensively about prospects for meaningful and procreative research ideas for this facility. The present contribution attempts to review some results of preliminary analysis of chances and challenges for novel, useful and (maybe) realistic program in the area of positron physics, surely interesting topic, but little neglegted in existing materials of the project. As input parameters for our study, planned characteristics of the pillar ELI Beamlines are supposed.

In the first part of the presentation (Laser-driven positron sources), possibilities for positron generation using a multibeam system with high repetition rate, maximum energy of several hundred Joules, and intensity 10^20 - 10^24 W/cm^2 will be considered. Only Bethe-Heitler and trident mechamisms can be expected as a basis for intense positron generation in this range of parameters. Various types of potential target arrangements will be reviewed. Problems of focusing, spectrum adjustment, deceleration, cooling and positronium production will be adressed. Questions related to realistic simulation of such system will be formulated.

The second part (Positron beam interactions) will be devoted to the discussion of potential, reasonably realistic experiments with medium-energy positron beams. Special attention will be paid to two specific proposals: (1) Laboratory study of positron interaction and annihilation in interstellar medium (ISM). Application of gas / dust targets will be considered, problems of scaling of such experiments will be tackled. (2) Nuclear excitation in the positron-atomic electron annihilation (process NEPEA). A large discrepancy between theoretical predictions and experimental results for this effect exists, new types of experiments would be useful. Some other chances for research with medium-energy positrons will be also shortly mentioned.

In the third part (Pair systems and mirror matter) a more visionary topics will be adressed. Problems and potential solutions in two areas of frontier physics including positrons will be denoted: (1) Lepton plasma and positronium Bose-Einstein condensate (BEC). Uncertainties connected with this risky / highly rewarding theme of research will be looked on. (2) Mirror dark matter search via the invisible decay of ortho-positronium. A version of an experimental setup using high-yield pulsed positron source will be debated. Preparatory phase program to study / solve technical tasks and diagnostics for this area will be outlined.

This research has been supported by the Research Program No. 6840770022 of the Ministry of Education, Youth and Sports of the Czech Republic

8080B-49, Session 17

TBA

W. Sandner, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

No abstract available

8080B-58, Session 17

On the design of experiments for the study of extreme field limits in the ultra-relativistic interaction of electromagnetic waves with plasmas

S. V. Bulanov, T. Z. Esirkepov, Japan Atomic Energy Agency (Japan)

We discuss how to conduct the experiments on the collision of laser light and high intensity electromagnetic pulses generated by relativistic flying mirrors, with electron bunches produced by a conventional accelerator and with laser wake field accelerated electrons for studying extreme field limits in the nonlinear interaction of electromagnetic waves. The regimes of dominant radiation reaction, which completely changes the electromagnetic wave-matter interaction, can be revealed in the laser plasma experiments. This will result in a new powerful source of ultra short high brightness gamma-ray pulses. A possibility of demonstration of the electron-positron pair creation in vacuum in a multi-photon processes can be realized. This will allow modelling under the terrestrial laboratory conditions the neutron star magnetospheres, the cosmological gamma ray bursts and Leptonic Era of the Universe.

8080B-59, Session 17

Effects of quantum vacuum in ultra-intense laser fields and their simulation

H. Ruhl, Ludwig-Maximilians-Univ. München (Germany)

No abstract available

8080B-60, Session 17

“Rogue” waves in plasma and multi-hysteresises due to relativistic nonlinearities

A. E. Kaplan, The Johns Hopkins Univ. (United States)

An overdense plasma layer irradiated by an intense light can exhibit dramatic nonlinear-optical effects due to a relativistic mass-effect of free electrons: highly-multiple hysteresises of reflection and transition, and emergence of gigantic “rogue waves”. Those are trapped quasi-

soliton field spikes inside the layer, sustained by an incident radiation with a tiny fraction of their peak intensity once they have been excited by orders of magnitude larger pumping. The phenomenon is feasible in plasma layers of just a few wavelength thick and persists even in the layers with “soft” boundaries, as well as in a semi-infinite plasma with low absorption.

8080B-61, Session 18

Radiation damping of relativistic electrons at laser hole-boring in overdense plasmas

T. Schlegel, Technische Univ. Darmstadt (Germany)

No abstract available

8080B-62, Session 18

Absorption and contrast studies at relativistic intensities

D. Neely, Rutherford Appleton Lab. (United Kingdom)

No abstract available

8080B-63, Session 18

Ultra-strong laser pulses: quantum radiative reaction and streak-camera for gamma-rays via pair production

K. Z. Hatsagortsyan, Max-Planck-Institut für Kernphysik (Germany)

No abstract available

Plenary Presentations

Photonics in the EU: Opportunities and Challenges

Thomas Skordas, Head of Photonics Unit, DG INFSO-European Commission, Belgium; Ronan Burgess, Head of Sector, Photonics Unit, DG INFSO-European Commission, Belgium

The talk will address developments in European photonics and the challenges that the research community and the industry are facing in a very competitive global market. In particular, the European Commission's strategy for Research, Development and Innovation in photonics will be highlighted. Topics that will be covered include: the role of photonics as one of Europe's Key Enabling Technologies, information on recent and upcoming calls for R&D proposals in the area as well as on the preparation of the new Framework Programme 8 and the potential role of photonics.

Molecular and Biomolecular/Nanoparticle Hybrids for Nanotechnological Applications

Itamar Willner, The Hebrew University of Jerusalem, Institute of Chemistry, Israel

Metal or semiconductor nanoparticles exhibit unique electronic, catalytic or optical size-controlled properties. The functionalization of the nanoparticles with molecular or biomolecular capping units lead to hybrid systems that combine the features of the composite materials. These hybrid systems are implemented to develop electronic or optical sensors for clinical diagnostics, environmental control, and homeland security, and to design nanoscale devices via bottom-up approaches. The talk will review the advances of our laboratory in developing new electronic and sensing platforms, the fabrication of nanocomposites for stimuli-controlled uptake and release of substrates ("nano-sponges") and the preparation of metallic nanowires and nano-circuitry.

The Frontier of High Field Science

Toshiki Tajima, Ludwig Maximilian Univ. Munich, Germany, Chair of Scientific Advisory Committee of Extreme Light Infrastructure

The concept of laser acceleration with relativistic laser has nurtured the growth of high field science and intense lasers. These in turn bear relativistic optics in which the relativistic dynamics helps the relativistic coherence emerge, because particles cohere in its relativistic velocity at c. Laser acceleration applications now abound with novel radiation sources of various kinds, compact accelerators for chemical and medical uses, high energy physics accelerators, and for fundamental physics exploration purposes. We show an example of precision experiment at extremely high energies (such as PeV by laser acceleration) with time resolutions as small as attoseconds. In this case we no longer need to stick to the high luminosity constraint, looking at the validation of relativity itself. We also show an ever shorter scale science such as in zeptoseconds and even yoctopseconds by employing the properties of vacuum under intense laser fields. Along this we (Gerard Mourou and I) have stumbled into a realization (Conjecture) that the layer of nonlinearities of matter provides the reason why the pulse length can be shortened if and when we employ greater intensity of laser to drive coherent radiation from matter.

Laser Fusion and The National Ignition Facility: Bringing Star Power to Earth

Christopher P. J. Barty, Chief Technology Officer, National Ignition Facility and Photon Science Directorate, Lawrence Livermore National Lab., United States

At 1.8 Mega-Joules, the National Ignition Facility (NIF) at the Lawrence Livermore National Laboratory is the world's highest-energy laser system. NIF exceeds the next largest laser system by nearly two orders of magnitude. Designed and constructed for the U.S. Department of Energy, NIF will be the first laser facility to achieve controlled nuclear fusion ignition and burn in the laboratory, a hallmark event for science in the 21st century.

The development of NIF has required numerous advances in science and technology. These range from technologies for rapid manufacturing of advanced laser glass and meter-scale nonlinear crystals to the fundamental materials understanding of optical damage and the development of nano- and micro-scale materials systems for fusion targets. The demonstration of fusion ignition on NIF will open the possibility of clean, limitless, fusion power from a NIF-like inertial fusion process, so-called Laser Inertial Fusion Energy (LIFE). LIFE, however, will require increasing NIF's repetition rate from one shot every four hours to approximately 10 shots per second. This ambitious goal presents an entirely new set of challenges, including the development of novel, high power laser architectures, laser glasses and ceramics with high thermal conductivity, final optics with resistance to high neutron fluxes, and the development of fusion chamber materials capable of surviving in a high neutron and x-ray radiation environment.

This talk will review the development of NIF and the associated challenges, the architecture and operation of NIF, the status of the National Ignition Campaign to achieve fusion burn and gain with NIF, and introduced the concept and challenges for solving the world's energy needs with LIFE.

HiPER: The European Route to Laser Energy

Chris Edwards, HiPER Fusion Project Director, Central Laser Facility, Science and Technology Facilities Council, United Kingdom

HiPER is a European Consortium of 26 institutions from 10 nations dedicated to developing the route to commercially viable power from Laser fusion. Currently in its Preparatory Phase, HiPER is assessing options for the development of the required technology including the laser driver, mass production of the fusion target and target area technology.

This talk will outline the need and benefits of Laser Energy as a future source of baseload electricity generation. It will describe the progress made in this field within Europe to date and describe the future route to realisation of this technology following the proof of principle demonstration at the National Ignition Facility.

HiPER: preparing for the next phase

John L. Collier, Rutherford Appleton Lab. (United Kingdom)

Overview of the LULI diode-pumped laser chain proposal for HIPER kJ beamlines

Jean-Christophe F. Chanteloup, Antonio Lucianetti, Daniel Albach, Thierry Novo, Ecole Polytechnique (France)

A major challenge the HiPER project is facing is to derive laser architectures satisfying simultaneously all HiPER requirements; among them, high wall-plug efficiency (15 to 20%) and repetition rate (5 to 10 Hz) are the most challenging constraints. We will describe the active mirror Yb:YAG amplifier proposal from LULI. Emphasis will be put on cooling concept with sub-atmospheric pressure static cell.

HiPER laser reference design

Bruno Le Garrec, Commissariat à l'Énergie Atomique (France); Mike Tyldesley, Rutherford Appleton Lab. (United Kingdom); Chris Edwards, Science and Technology Facilities Council (United Kingdom); John L. Collier, Rutherford Appleton Lab. (United Kingdom)

HiPER is a proposed European High Power laser Energy Research facility dedicated to demonstrating the feasibility of laser driven fusion as a future energy source. The HiPER project intends to demonstrate fast ignition of laser-driven targets by mean of a multi-beam, multi-ns laser pulse of about 250-300 kJ for implosion and a short pulse of about 100 kJ delivered in 15 ps for ignition. In this type of direct-drive inertial confinement fusion, the "ignitor" shock can also be launched by a 60-80 kJ power spike at the end of the laser pulse.The HiPER project is in a preliminary phase and a risk assessment is being conducted for a generic beamline concept - this is based on an anticipated requirement for a single beamline drawn from the best available knowledge we have to date of the fusion physics requirement. This presentation will give a general overview of the HiPER laser, technical details about the laser architecture, the laser gain medium and the final optics assembly.

Optimised design for a 1 kJ diode-pumped solid-state laser system

Paul D. Mason, Klaus Ertel, S. Banerjee, Paul J. Phillips, Cristina Hernandez-Gomez, John L. Collier, Rutherford Appleton Lab. (United Kingdom)

More and more projects and applications require the development of kJ-class laser systems operating at multi-Hz repetition rate and high wall-plug efficiency (greater than 10%), which is only possible using diode pumped solid state laser (DPSSL) technology. These lasers will either be used directly for generating plasmas, e.g. in the context of inertial fusion energy (IFE) production, or for pumping short-pulse amplifiers such as OPCPA or Ti:Sapphire systems. To achieve efficient diode-pumped operation we have selected ceramic Yb:YAG as the gain medium, as it offers a respectable gain cross section, allowing simple and efficient energy extraction, and a reasonable fluorescence lifetime (of order 1 ms), minimising the number and cost of pump diodes required. It is also available in large optical apertures (up to 15 cm), with good optical quality, and offers the potential for composite structures for management of amplified spontaneous emission (ASE). Efficient operation can be achieved by cooling to low temperatures (? 175 K), reducing reabsorption losses, whilst further improving thermo-mechanical and thermo-optical properties necessary for handling high average powers. In this paper we present performance modelling of a 1 kJ DPSSL amplifier system, based on cryogenic gas cooled multi-slab ceramic Yb:YAG technology. The proposed beamline concept is based on a pair of identical amplifier heads configured in a 4-pass architecture, similar to that used in NIF or LMJ. The design has been optimised to achieve maximum optical-to-optical efficiency for amplification of nanosecond pulses, at a representative level of optical loss, whilst minimising the level of ASE and ensuring the overall B integral is kept at an acceptable level. To test the amplifier design a lower energy prototype system, DiPOLE, is currently under development at the Central Laser Facility. A progress update on the status of this system will be presented.

Overview of the FSU diode concept for HiPER and the Polaris facility

Joachim Hein, Friedrich-Schiller-Univ. Jena (Germany)

Overview of fusion reactor design and fusion technology

Manolo Perlado, Univ. Politécnica de Madrid (Spain)

Target and repetition rate fusion chamber systems

Bedrich Rus, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Recent progress made in the SBS PCM approach to self-navigation of lasers on direct drive IFE targets

Milan Kalal, Ondrej Slezak, Czech Technical Univ. in Prague (Czech Republic); Hong Jin Kong, KAIST (Korea, Republic of); Elena R. Koresheva, P.N. Lebedev Physical Institute (Russian Federation); Sangwoo Park, KAIST (Korea, Republic of); Sergey A. Startsev, P.N. Lebedev Physical Institute (Russian Federation)

Current status of SBS PCM based IFE approach proposed recently as an alternative to the IFE classical approach is presented. This technology is of a particular importance to the direct drive scheme taking care of automatic self-navigation of every individual laser beam on the injected pellets without any need for final optics adjustments. An upgraded scheme was developed with a low energy illumination laser beam (glint) entering the reactor chamber through the same entrance window as used subsequently by the corresponding high energy irradiation laser beam. Experimental verification of this improved design was performed using a complete setup including a pellet-at this stage realized by a static steel ball of 4 mm in diameter. The pellet survival conditions between its low energy illumination and high energy irradiation were studied and the upper limits on the allowed energies absorbed for both DD and DT fuels were determined.

A novel single-shot, spectrally resolved X-ray imaging technique of ICF relevant plasmas

Luca Labate, C. A. Cecchetti, O. Ciricosta, Petra Koester, T. Levato, Leonida A. Gizzi, Intense Laser Irradiation Lab., INO/CNR (Italy)

A new diagnostic tool has recently been developed, which allows to get 2D images of X-ray sources with simultaneous energy encoded information. This is achieved by using a pinhole camera scheme in which a CCD camera, forced to operate in the single-photon regime, is used as a detector. The use of this method, initially limited to a single-pin-hole, multi-shot basis, has recently been extended to single-shot experiments typical of large scale installations using custom pin-hole arrays of sub-10 micron diameter. Preliminary tests have been carried out at the PALS facility and the diagnostics has been successfully employed in a PW environment in a recent experiment at RAL. The details of the method as well as some results form such recent experiments will be given.

High resolution Xray spectroscopy in fast electron transport studies

Petra Koester, Intense Laser Irradiation Lab./INO-CNR (Italy); Nicola Booth, The Univ. of York (United Kingdom); C. A. Cecchetti, Intense Laser Irradiation Lab./INO-CNR (Italy); Hui Chen, Lawrence Livermore National Lab. (United States); R. G. Evans, Imperial College London (United Kingdom); Gianluca Gregori, Univ. of Oxford (United Kingdom); Luca Labate, T. Levato, Intense Laser Irradiation Lab./INO-CNR (Italy); Y. B. Li, Imperial College London (United Kingdom); M. Makita, Queen's Univ. Belfast (United Kingdom); J. Mithen, Univ. of Oxford (United Kingdom); C. Murphy, Imperial College London (United Kingdom); M. M. Notley, Rajeev P. Pattathil, Rutherford Appleton Lab. (United Kingdom); David Riley, Queen's Univ. Belfast (United Kingdom); N. C. Woolsey, The Univ. of York (United Kingdom); Leonida A. Gizzi, Intense Laser Irradiation Lab./INO-CNR (Italy)

A detailed knowledge of the physical phenomena underlying the generation and the transport of fast electrons generated in highintensity lasermatter interactions is of fundamental importance for the fast ignition scheme for inertial confinement fusion. Here we report on an experiment carried out with the VULCAN Petawatt beam and aimed at investigating the role of collisional return currents in the dynamics of the fast electron beam. To that scope, in the experiment counterpropagating electron beams were generated by doublesided irradiation of layered target foils containing a Ti layer. The experimental results were obtained for different time delays between the two laser beams as well as for singlesided irradiation of the target foils. The main diagnostics consisted of two bent mica crystal spectrometers placed at either side of the target foil. Highresolution Xray spectra of the Ti emission lines in the range from the Ly? to the K? line were recorded. In addition, 2D Xray images with spectral resolution were obtained by means of a novel diagnostic technique, the energyencoded pinhole camera, based on the use of a pinhole array equipped with a CCD detector working in singlephoton regime. The spectroscopic measurements suggest a higher target temperature for wellaligned laser beams and a precise timing between the two beams. The experimental results are presented and compared to simulation results.

Can proton radiography be used to image imploding target in ICF experiments?

Luca Volpe, Dimitri Batani, Univ. degli Studi di Milano-Bicocca (Italy); Benjamin Vauzour, Phillipe Nicolai, Joao J. Santos, Fabien Dorchies, Claude Fourment, Sébastien Hulin, C. Regan, Univ. Bordeaux 1 (France); Frederic Perez, Sophie D. Baton, Michel Koenig, Ecole Polytechnique (France); Kate L. Lancaster, Marco Galimberti, Robert Heathcote, Martin K. Tolley, Chris Spindloe, Rutherford Appleton Lab. (United Kingdom); Petra Koester, Luca Labate, Leonida A. Gizzi, Intense Laser Irradiation Lab./INO-CNR (Italy); C. Benedetti, Andrea Sgattoni, Univ. degli Studi di Bologna (Italy); Maria Richetta, Univ. degli Studi di Roma Tor Vergata (Italy)

An experiment was done at the Rutherford Appleton Laboratory (Vulcan Laser Petawatt laser) to study fast electron propagation in cylindrically compressed targets, a subject of interest for fast ignition. This was performed in the framework of the experimental road map of HiPER (the European High Power laser Energy Research facility Project). In the experiment, protons accelerated by a ps-laser pulse were used to radiograph a 220 ?m diameter cylinder (20 ?m wall, filled with low density foam), imploded with ~200 J of green laser light in 4 symmetrically incident beams of pulse length 1 ns. Point projection proton backlighting was used to get the compression history and the stagnation time. Detailed comparison with 2D numerical hydro simulations has been done using a Monte Carlo code adapted to describe multiple scattering and plasma effects and with those from hard X-ray radiography. These analysis shows that due to the very large mass densities reached during implosion processes, protons traveling through the target undergo a very large number of collisions which deviate protons from their original trajectory reducing Proton Radiography resolution. Here we present a simple analytical model to study the Proton Radiography performance as a function of the main experimental parameters such as proton beam energy and target areal density. This approach leads to define two different criteria for PR resolution (called "strong" and "weak" condition) describing different experimental conditions. Finally numerical simulations using both Hydrodynamic and Monte Carlo codes are presented to validate analytical predictions..

Active mirror amplifying laser chain for HIPER laser driver

Antonio Lucianetti, Ecole Polytechnique (France)

Overview of STFC diode-pumped kJ-class amplifier concept for HiPER

Paul D. Mason, Klaus Ertel, Saumyabrata Banerjee, Jonathan Phillips, Cristina Hernandez-Gomez, John L. Collier, Rutherford Appleton Lab. (United Kingdom)

We present an overview of the STFC conceptual design of a diode-pumped cryogenic kilo-Joule class Yb:YAG amplifier as a building block towards a mega-Joule class source for inertial fusion energy (IFE) projects such as HiPER

HiPER target studies: first steps towards the design of high gain, robust, scalable direct-drive targets with advanced ignition schemes

Stefano Atzeni, Univ. degli Studi di Roma La Sapienza (Italy); G. Schurtz, Univ. Bordeaux 1 (France)

In a laser-driven inertial confinement fusion power plant targets with energy gain (ratio of fusion energy to laser energy) about 100 will be burnt at a rate of 5-20 Hz. The laser driver will deliver accurately time- and space-shaped pulses of energy of 3-5 MJ at the above rate. Advanced ignition schemes (fast ignition and shock ignition) have the potentials to achieve such a large gain. In addition, shock ignition targets can in principle have simple structure, suitable to high rep-rate operation and the demanding reactor chamber environment. Target studies in the frame of the HiPER project aim to design robust targets ignited by one of the previously mentioned schemes. We began by designing a very simple target which could allow for ignition demonstration with a few hundred kJ laser, and can be scaled at higher energy and gain. We have determined the requirements for fast and shock ignition, and have identified crucial issues that have to be addressed experimentally. We have also developed (and are developing) new models and codes to investigate topics such as fast electron generation and transport in fast ignition targets, and non-local electron transport in the corona of shock-ignition targets. We have also investigated irradiation schemes, target symmetry and stability issues, sensitivity to parameter changes, requirements for beam delivery and focussing for target positioning. At present we are working along three main directions: increase target robustness (also taking into account target manufacturing and delivery issues), scale to somewhat greater laser energy (to make the design less marginal), and designing targets that might be tested on already existing facilities (NIF), or at an advanced state of construction (LMJ). Work supported by Italian MIUR and HiPER STFC funding

HiPER targetry: production and strategy

Author(s): Martin K. Tolley, Rutherford Appleton Lab. (United Kingdom)

The HiPER project is moving into an R&D phase with an increasingly clear vision of the stages required to demonstrate inertial fusion

energy (IFE) as a power source. One of the major technical challenges will be to demonstrate the production and delivery to chamber of microtargets. The project baseline targets will be reviewed along with other Targetry-relevant system requirements. An update will be given of the current status of the HiPER Targetry workpackage reviewing the coordinated range of progress which has been made. A forward strategy will then be presented of the Targetry technology development plan. Several novel technologies have the potential for producing the high numbers of ultraprecision microtargets which will be required. Consequently the delivery plan is complex and it will be presented in a comparative way whilst also focussing on risk reduction. There will also be a discussion of Targetry from a mass production systems viewpoint.

Overview of injector, cryogenic and tritium considerations of target fabrication

Didier Guillaume, Commissariat à l'Énergie Atomique (France)

Shock-ignition targets: symmetry, stability, robustness

Stefano Atzeni, A. Schiavi, A. Marocchino, A. Giannini, Univ. degli Studi di Roma La Sapienza (Italy)

Shock ignition (SI) is a promising approach to inertial confinement fusion (ICF), in which formation of a compressed fuel assembly and fuel ignition are achieved using two separate laser pulses. The first pulse generates a dense fuel assembly with a central hot spot, which, however, is not sufficient to achieve ignition. Ignition is instead triggered by a second, intense laser pulse, launched towards the end of compression. Such a pulse generates a strong, inwards moving shock, which is further amplified by spherical convergence. The collision between this shock and the rebouncing shock coming from the centre causes the additional heating and compression of the hot spot needed for ignition. Given the potentials of this new scheme, we have studied some aspects of the robustness of the shock ignited targets considered in the HiPER project. The sensitivity to variation of parameters and errors or imperfections has been analysed by means of one-dimensional and two-dimensional numerical simulations.
An operating window for the parameters of the ignition laser spike is described; the threshold power depends on beam focusing and synchronization with the compression pulse. The time window for spike launch widens with beam power, while the minimum spike energy is independent of spike power. A large parametric scan (several thousand simulations) indicates good tolerance (at the level of a few percent) to target mass and laser power errors. It is shown that the growth of both Richtmyer-Meshkov and Rayleigh-Taylor instability (RTI) at the ablation front is reduced by laser pulses with an adiabat-shaping picket. 2D simulations indicate that the strong igniting shock wave plays an important role in reducing deceleration-phase RTI growth. Instead, the high hot-spot convergence ratio (ratio of initial target radius to hot-spot radius at ignition) makes ignition highly sensitive to target mispositioning. Work supported by Italian MIUR and HiPER STFC funding

Experimental results performed in the framework of the HiPER European Project

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In 2006 the HiPER Project (European High Power laser Energy Research facility) has been included by ESFRI (the European Strategy Forum on Research Infrastructures) in the European roadmap for Research Infrastructures. The HiPER Project concerns the study, and the following realization, of a high energy laser facility for studies on the production of energy via inertial confinement fusion. HiPER will represent a possible follow up to the National Ignition Facility (NIF), the biggest laser in the world located at the Livermore National Lab in the US, which has recently started the Ignition Campaign aimed at demonstrating the scientific feasibility of nuclear fusion by the end of 2012. In the talk, I will first present the goals and the structure of the HiPER project, and then present the results of some experiments conducted within the Working Package 10 (Fusion Experimental Programme) of the HiPER Project. These experiments concern the study of "Advanced Ignition Schemes" based on the Fast Ignition and the Shock Ignition Approaches to Inertial Fusion. These schemes are aimed at achieving a higher gain, as compared to the classical approach which is used in NIF, as required for future reactors, and making fusion possible with smaller facilities. The experiments related to Fast Ignition were performed at the RAL (UK) and LULI (France) Laboratories and were addressed to study the propagation of fast electrons (created by a short-pulse ultra-high-intensity beam) in compressed matter, created either by cylindrical implosions or by compression of planar targets by (planar) laser-driven shock waves. The experiment on Shock Ignition was performed at PALS (Prague, Czech Rep) and investigated the laser-plasma coupling in the 1016 W/cm2 intensity regime, addressing in particular the role of parametric instabilities in the extended plasma corona, the ability to create strong shocks (in the hundreds of MBar range), the role of fast electrons produced during the interaction.

Results of recent Shock ignition experiments on the Omega facility

G. Schurtz, Univ. Bordeaux 1 (France)

Computer simulations of the experiments at RAL, LULI, and PALS carried out under HiPER, including those performed at ILE, Japan. Numerical comparison of high density plasmas of HiPER experiments

Author(s): Yongjoo Rhee, Korea Atomic Energy Research Institute (Korea, Republic of)

Since the initial launch of HiPER programme, many experiments have been carried out to investigate the properties of high density plasmas related to laser fusion. Especially topics like compression of plasmas, proton/X-ray radiography, electron transport, plasma acceleration and collimation, etc have been studied, which are closely related to fast ignition or shock ignition. In this report comparison of computer simulations applied to the experiments at RAL(UK), LULI(France), PALS(Czech Republic), and ILE(Japan) as well as at KAERI with 30TW 30fs Ti:Sapphire laser will be given. Temporal evolution of densities, electron temperatures, compression/implosion velocities, etc will be included in the discussion.

Plasma parametric instabilities study in shock ignition relevant regime

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Inertial Confinement Fusion Shock Ignition approach relies on a very strong shock created by a laser pulse at intensity of the order of 1016W/cm2. In this context an experimental campaign at Prague Asterix Laser System (PALS) has been performed. Two beam have been used, the first one to create an extended preformed plasma (scale length of the order of hundreds um), the second pulse was used to create the shock. Different diagnostics were used to characterize different physical output of the experiment mainly focused on study of the shock breakout generated from a planar target, on laser-plasma coupling and parametric instability development. This document is focused on the data, and their analysis, collected with the back-scattering diagnostic devoted to measure the back-reflected energy, and to characterize the parametric instabilities as Brillouin, and Raman. By correlating calorimetry and spectroscopic measurements a study of the laser-plasma coupling in relevant Shock Ignition intensity regime is presented. Based on spectral measurements of back reflected light an almost well defined region for laser energy absorption has been identified. Moreover, experimental data have shown that parametric instabilities do not play a strong role on the laser plasma coupling. By monitoring the back reflected light from the interaction region we found that only less than 5% of the total incoming laser energy was back reflected, and that only a little part of that light was coming from parametric instabilities.

Results of recent PALS experiment

Jaroslav Nejdl, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

On the HiPER fundamental science programme

E. L. Clark, AWE (United Kingdom); Christos Kamperidis, Nektarios Papadogiannis, Michael Tatarakis, Technological Education Institute of Crete (Greece)

The HiPER infrastructure will be a uniquely valuable tool for scientific discovery because it will be able to generate extreme matter conditions similar to those existing in our sun and the universe. The existence of long and short laser pulses combined with ultra-high intensity beams in one unique infrastructure is fascinating and will allow the study of new branches of physics. HiPER is therefore being designed to enable a broad area of new science studies including warm dense matter studies, astrophysics in the laboratory, extreme mater studies (under extreme magnetic and electric fields), highly nonlinear laser plasma interactions etc. The scope of this presentation is to present the progress of work on: a) the fundamental science target area design b) the shielding requirements for the fundamental science programme c) the laser specifications for the fundamental science programme d) the training plan of HiPER Contact information: m.tatarakis@chania.teicrete.gr