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10227-1, Session 1

All-dielectric resonant nanophotonics and high-efficient metasurfaces *(Invited Paper)*

Yuri S. Kivshar, Australian National Univ (Australia)

Rapid progress in plasmonics is driven by the ability to enhance near-field effects with subwavelength localization of light. Recently, we observe the emergence of a new branch of nanophotonics aiming at the manipulation of strong optically-induced electric and magnetic Mie-type resonances in dielectric and semiconductor nanostructures with high refractive index. Unique ad-vantages of dielectric resonant optical nanostructures over their metallic counterparts are low dissipative losses, low heating, and the enhancement of both electric and magnetic fields. In this talk, I will review this new emerging field of nanophotonics and metasurfaces and demonstrate that Mie-type resonances in high-index dielectric nanoparticles and subwavelength structures can be exploited for new physics and novel functionalities of photonic structures especially in the non-linear regime.

10227-2, Session 1

Tunable spin-directional coupling for surface localized waves with anisotropic metasurface

Oleh Y. Yermakov, Andrey A. Bogdanov, Ivan V. Lorsh, ITMO Univ. (Russian Federation); Konstantin Y. Bliokh, RIKEN Ctr. for Emergent Matter Science (Japan); Yuri S. Kivshar, ITMO Univ. (Russian Federation) and The Australian National Univ. (Australia)

Recently, it has been already investigated that eigenmodes spectrum of hyperbolic metasurface consists of two hybrid TE-TM polarized modes [1]. Hybridization, as the consequence of anisotropy and accidental degeneracy of the eigenmodes, breaks spin-momentum locking of evanescent waves [2]. We have shown that the surface modes are characterized by the finite longitudinal angular momentum together with the transverse one [3]. This finding is in a sharp contrast to the properties of conventional surface waves localized at interfaces of isotropic materials, which carry purely transverse spin [4,5], and to the bulk waves in free space, which carry purely longitudinal spin.

The directivity of surface plasmons at the hyperbolic metasurfaces can be controlled with high flexibility, allowing almost unidirectional propagation of surface waves excited by a point source. Recently, it was also shown [6-8] that evanescent waves exhibit robust transverse coupling between their spin angular momentum and propagation direction. Tunability of spin-directional coupling results in the directional excitation of the surface waves.

These results can significantly enrich various spin-orbit interaction phenomena, which currently attract enormous attention to the near-field optics and spin-orbit photonics [8,9]. Scientific and practical significance of the results highlights a number of potential applications in optical information technologies, optoelectronic and optomechanical devices, biological sensors, rapidly emerging field of spin-optronics etc.

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10227-3, Session 1

Dynamical pixel manipulation of metasurfaces

Jin-Qian Zhong, National Tsing Hua Univ. (Taiwan)

Two-dimensional (2D) metamaterials or known as metasurfaces have attracted researchers' attention due to their capability to manipulate the amplitudes, phases and polarization states of incident electromagnetic waves by conferring extra phase different phase at different positions through a super cell that is composed of different oriented structures. In other words, metasurfaces can achieve beam steering and wave shaping by imparting local, gradient phase shift to the incoming waves. With these abilities, metasurfaces can be applied to applications such as ultrathin invisibility cloaks, metasurface holograms, planar lenses and a vortex generator. With the above mentioned advantages and applications of metasurfaces, yet, all the demonstrated metasurfaces possess a main insufficiency that once the metasurfaces are designed and fabricated, their optical properties are then fixed without any chance for further manipulation, which limits their versatility in practical applications. Moreover, although some researchers employed dynamically changeable materials to achieve an active metasurface, such manipulation can only change the overall performance such as an operating frequency instead of changing the provided phase on each pixel of a metasurface. To solve this issue, we employ liquid crystal integrated with a metasurface and the combination could be thus be dynamically tuned via electric bias on each pixel of liquid crystals. Through this setup, we can alter the polarization state of the incident electromagnetic wave dynamically and thus manipulate the extra phase provided by each pixel. In this combination, liquid crystal is employed to change the incident polarization from 0 to 360-degree and the metasurface is designed to achieve four different output signals including phase modulated linear- and circular-polarized light and amplitude-modulated linear- and circular-polarized light. Meanwhile, the metasurfaces could also control the transmission efficiency of the device.

10227-5, Session 1

Plasmon-induced transparency-like behavior at terahertz region via dipole oscillation detuning in a hybrid planar metamaterial

Zhenyu Zhao, Shanghai Normal Univ. (China)

We investigate a plasmon-induced transparency (PIT)-like behavior at terahertz (THz) region induced by resonance detuning in a hybrid planar metamaterial (MM). Each unit cell of the MM contains two types of dipole oscillation resonators: a cut-wire and a couple of U-shaped resonators in mirror symmetry. The hybridization of above resonators splits the single resonance mode into two side modes in THz transmission spectrum. The side modes are found out to induce negative group delays of incident THz wave-packet. The distribution of surface currents and electric energy reveals that the near-field coupling between cut-wire and U-shape resonators results in inductive-capacitive (LC) resonance, which dominates the low frequency side mode; while the high frequency side mode attribute to the triple dipole oscillations. The reduction of the length of cut-wire give arise to a dipole resonance detuning, which enhances the LC resonance via near-field coupling, while attenuates the constructive inference of triple dipole oscillators. The retrieved complex dielectric functions indicate the evolution of LC resonance and triple dipole oscillations. By control the dipole resonance detuning appropriately, a man-made transparent tip can be created in between the two side modes. However, such a transparent tip is unable to induce negative group delay. Aforementioned PIT-like behavior can support the design of hybrid planar MMs in application of two-band notch filters or multi-channel buffer in the THz-region.

10227-6, Session 2

Light-matter interaction in planar plasmonic and metamaterial systems: equilibrium and non-equilibrium effects *(Invited Paper)*

Kurt Busch, Humboldt University Berlin (Germany)

Certain plasmonic and derived systems such as hyperbolic metamaterials promise large and broadband enhancements of the photonic density of states which, in turn, lead to corresponding enhancements of light-matter interaction. In this talk, recent theoretical advances regarding the most simple settings, i.e., planar materials and one- and zero-photon effects (spontaneous emission, Casimir-Polder force, and quantum friction) will be discussed with an emphasis regarding the appropriateness of different material models [1,2] and the validity of certain approximation schemes such as the Markov and the local thermal equilibrium approximation [3,4,5].

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10227-7, Session 2

Hyperbolic waveguide for long-range heat transport

Svend-Age Biehs, Carl von Ossietzky Univ. Oldenburg (Germany); Philippe Ben-Abdallah, Lab. Charles Fabry (France) and Ctr. National de la Recherche Scientifique (France) and Univ. Paris-Saclay (France)

When two objects at two different temperatures are close enough, near-field effects due to tunneling of evanescent waves between them can lead to a radiative transfer beyond the Planck limit [1]. However at large separation distances (i.e. in the far-field regime) the transfer of energy which results exclusively from propagative photons cannot exceed this limit. In this presentation we show in the framework of fluctuational electrodynamicsthat using hyperbolic media [2,3] to connect a hot to a cold body we can in principle transport the near-field energy over distances much larger than the thermal wavelength and observe a surperPlanckian transfer at long separation distance [4].

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10227-8, Session 2

On-chip near-wavelength diffraction gratings for surface electromagnetic waves

Evgeni A. Bezus, Vladimir V. Podlipnov, Andrey A. Morozov, Leonid L. Doskolovich, Image Processing Systems Institute (Russian Federation) and Samara Univ. (Russian Federation)

Since the fabrication of first diffraction gratings and first observation of resonances in gratings more then a century ago, diffraction gratings have found various applications as spectral filters, beam splitters, radiation absorbers etc. While the optical properties of the gratings have been extensively studied in the diffraction (large-period) and in the effective-medium regimes, the near-wavelength regime (the case when the wavelength of the incident light is close to the grating period) has attracted considerable research interest over the past couple of decades. In this regime, gratings demonstrate the most interesting optical properties such as high quality-factor resonances or broadband high reflection or transmission.

In our recent paper, we have for the first time theoretically and numerically investigated on-chip near-wavelength diffraction gratings for the best-known type of surface electromagnetic waves — namely, for surface plasmon polaritons propagating at interfaces between metal and dielectric media [Bezus et al., Opt. Lett. 40(21), 4935–4938 (2015)]. It was shown that the diffraction of surface plasmon polaritons on on-chip gratings is qualitatively, and, under certain conditions, quantitatively close to the diffraction of TE-polarized plane electromagnetic waves on conventional gratings.

In the present work, we demonstrate our new results on plasmonic gratings. In particular, plasmonic grating-based beam splitters and deflectors with subwavelength footprint in the propagation direction are presented. The application of several techniques for parasitic (out-of-plane) scattering suppression to these plasmonic gratings is discussed. Using full-wave simulations within the framework of aperiodic Fourier modal method, it is shown that with the scattering suppression the efficiency of the considered on-chip gratings exceeds 85%. Along with the theoretical and numerical results, we present proof-of-concept experimental results confirming the functionality of plasmonic beam splitters and deflectors. The investigated gratings were fabricated from resist on a silver film using electron beam lithography and characterized using the leakage radiation microscopy technique. The obtained experimental results are in good agreement with the performed numerical simulations.

The extension of the on-chip gratings concept to other platforms such as planar waveguide modes and Bloch surface waves propagating at interfaces between photonic crystals and homogeneous media is also discussed. The proposed on-chip gratings may find application in the design of systems for optical information transmission and processing at the nanoscale.

10227-9, Session 2

On-chip phase-shifted Bragg gratings and their application for spatiotemporal transformation of Bloch surface waves

Leonid L. Doskolovich, Image Processing Systems Institute (Russian Federation) and Samara National Research Univ. (Russian Federation); Evgeni A. Bezus, Dmitrii A. Bykov, Nikita V. Golovastikov, Image Processing Systems Institute (Russian Federation) and Samara Univ. (Russian Federation)

Bloch surface waves (BSW) are surface electromagnetic waves propagating along the interfaces between a photonic crystal and a homogeneous medium or between two different photonic crystals. Along with surface plasmon polaritons (SPP), they are considered as potential candidates for the utilization in novel optical information processing devices as information carriers, as well as in other applications such as chemical and biological sensors. As opposed to SPP, BSW are supported by all-dielectric structures, so the absorption losses upon the surface wave propagation can be negligibly small.

In this work, we study numerically and theoretically phase-shifted Bragg gratings (PSBG) for BSW. The studied on-chip structures consist of a set of dielectric ridges located on the 1D photonic crystal surface, the height of which is chosen so that they encode the required distribution of the effective refractive index. Similarly to conventional PSBG, on-chip PSBG consists of two symmetrical on-chip Bragg gratings separated by a defect layer. Rigorous simulation results demonstrate that the surface wave diffraction on the proposed on-chip PSBG is close to the diffraction of

plane electromagnetic waves on conventional PSBG. For the considered examples, the correlation coefficient between the spectra of conventional PSBG and on-chip PSBG exceeds 0.99 in the vicinity of the resonance corresponding to the excitation of the eigenmodes localized in the defect layer.

Conventional PSBG are widely used for spectral filtering as well as for temporal and spatial transformations of optical pulses and beams including differentiation and integration of pulse envelope or beam profile. In our recent work [Opt. Express 24, 18828 (2016)], we described the general class of spatiotemporal transformations of optical signals implemented by PSBG. In the present work, we discuss the capability of on-chip PSBG to implement the operations of temporal and spatial differentiation of BSW pulses and beams as well as more general spatiotemporal transformations. The presented examples demonstrate the possibility of using the proposed structure for high-quality differentiation.

The obtained results can be applied for the design of the prospective integrated systems for on-chip all-optical analog computing.

10227-10, Session 2

Enhanced fluorescence emission using bound states in continuum in a photonic crystal membrane

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Metasurfaces are two-dimensional structures, arrays of scatterers with subwavelength separation or optically thin planar films, allowing light manipulation and enabling specific changes of optical properties [1], as for example beam-steering, anomalous refraction and optical-wavefront shaping [2]. Due to the fabrication simplicity, the metasurfaces offer an alternative to 3-D metamaterials and providing a novel method for optical elements miniaturization. High-quality metasurface optical elements based on titanium oxide, metals or silicon have been designed, leading to the realization of polarization optics, focusing mirrors, flat lenses, waveplates, holograms [3, 4, 5]. It has been demonstrated that a metasurface can support Bound States in Continuum (BIC), that are resonant states by zero width, due to the interaction between trapped electromagnetic modes [6, 7, 8]. The only possibility for these special Fano resonances to completely decouple from the continuum of the free-space modes is by mismatching their symmetries. However, fabrication imperfections partially break the symmetry of the lattice, allowing the coupling of the external incoming beam. At the bound state frequency, the electromagnetic field is ideally trapped by the structure with a divergent life-time. Experimentally, this involves very narrow coupled resonances, with a high Q-factor and an extremely large field intensity enhancement, up to 6 orders of magnitude larger than the intensity of the incident beam [6]. Here, we demonstrate that the field enhancement in proximity of the surface can be applied to boost fluorescence emission of probe molecules dispersed on the surface of a photonic crystal membrane fabricated in silicon nitride. Our results provide new solutions for light manipulation at the nanoscale, especially for sensing and nonlinear optics applications.

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10227-11, Session 3

New pathways for solitons and rogue waves in double negative and hyperbolic metamaterials *(Invited Paper)*

Allan D. Boardman, Univ. of Salford (United Kingdom); Jim McNiff, Original Perspectives Ltd. (United Kingdom)

This presentation involves the outcomes for solitons in new, exciting, and dramatic investigations of double negative and the nanostructured, modern, hyperbolic metamaterials. The latter are very popular now but they are asymmetric with an optic axis for which the orientation in any device can have an overwhelming influence. The influence of an optical axis orientation upon nonlinear behaviour is fascinating and is addressed her in the nonlinear domain through novel soliton behaviour. It will be emphasised The question of asymmetry has been referred very briefly before, without persuing any detail, through the comment that even small optical anisotropy is a much greater "enemy" of the perfect lens than absorption. The current hyperbolic metamaterial world is actually only partially served by investigations that incorporate some limited version of anisotropy. New, dramatic, pathways will be presented here involving the strong competitiveness of the optical axis orientation with other physical properties. The outcomes will, for example, be shown to circumvent unnecessary device design often executed to control absorption.

This report will also use solitons to look at the exciting feature called rogue waves and how they can be influenced by a nanostructured metamaterial environment. This is the first time that these waves will be examined for optic-axis driven metamaterials. Rogue waves are known in hydrodynamics as freak ocean waves that appear from nowhere, destroy shipping, and then disappear without trace. It is the nonlinear Schrodinger equation that provides a common soliton-based language and reveals shows that the mathematics of water waves and optical waves are the same. This great analogy between hydrodynamics and optics will be developed in a graphic manner and a broader study of optical rogue waves will show them also to have other analogies. The influence of metamaterials in a controlled application involving planar optical waveguides. with arbitrary optic axis orientations, will be presented and the positive impact upon the noise properties of optical devices will be assessed.

10227-12, Session 3

PT-axisymmetric VCSELS *(Invited Paper)*

Muriel Botey, Univ. Politècnica de Catalunya (Spain); Waqas Ahmed, Politècnica de Catalunya (Spain); Ramon Herrero, Univ. Politècnica de Catalunya (Spain); Kestutis Staliunas, , Institució Catalana de Reserca i Estudis Avançats (ICREA) (Spain)

Optical Parity-Time (PT-) symmetric systems support unusual properties when the symmetric coupling between internal modes is broken [1,2]. The simplest PT-symmetric 1D optical potential may be taken as: n(x)= n0 exp(iqx), which at resonance, asymmetrically couples the left-propagating mode, exp(-iq/2x), to the right-propagating mode exp(iq/2x), but not vice versa. The question that arises is what happens if such PT-symmetry condition is not met globally. A complex optical potential in the form: n(x)=n0 [cos(iq?x?)-i sin(iq?x?)] imposes a unidirectional coupling towards a selected position, x=0. Here, we propose a new class of PT-symmetric potentials with axial symmetry by radial dephased modulations of index and gain/loss: n(r)=n0[cos(iqr)-i sin(iqr)]. This axial potential intrinsically generates an exceptional central point leading to an extraordinary field enhancement and simultaneous confinement [3].

Broad aperture lasers, and VCSELs among them, are relevant laser sources however suffering from a major drawback: a poor beam quality due to the lack of an intrinsic transverse mode selection mechanism. Therefore, in particular, we explore the spatio-temporal field dynamics of a 2D complex PT-axysimmetric VCSEL which could have physical realizations with nowadays technology. Indeed, we show that field localization and enhancement is possible at r?=?0, revealing that this 2D axisymmetric system efficiently turns such microlasers into bright and narrow sources.

We expect the proposed PT-axisymmetric configuration to find remarkable applications for the beam quality emission improvement from VCSEL. Besides, the reported effect is universal, and could be extended to different linear or nonlinear physical systems, from optics to Bose condensates, or acoustics among others.

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10227-14, Session 3

Experimental demonstration of the surface state and optical topological phase transition of one dimensional hyperbolic metamaterial in Otto configuration

Chih Chung Wei, Leng-Wai Un, Ta-Jen Yen, National Tsing Hua Univ. (Taiwan)

One-dimension hyperbolic metamaterials (1DHMMs) possess marvelous and considerable applications: hyperlens, spontaneous emission engineering and nonlinear optics. Conventionally, effective medium theory, which is only valid for long wavelength limit, was used to predict and analyze the optical properties and applications. In our previous works, we considered a binary 1DHMM which consists of alternative metallic and dielectric layers, and rigorously demonstrated the existence of surface states and bulk-interface correspondence with the plasmonic band theory from the coupled surface plasmon point of view. In the plasmonic band structure, we can classify 1DHMMs into two classes: metallic-like and dielectric-like, depending on the formation of the surface states with dielectric and metallic material, respectively. Band crossing exists only when the dielectric layers are thicker than the metallic ones, which is independent from the dielectric constants. Furthermore, the 1DHMMs are all metallic-like without band crossing. On the other hand, the 1DHMMs with band crossing are metal-like before the band crossing point, while they are dielectric-like after the band crossing point. In this work, we measure the surface states formed by dielectric material and 1DHMMs with band crossing in Otto configuration. With white light source and fixed incident angle, we measure the reflectance to investigate the existence of the surface states of 1DHMMs with various thickness ratio of metallic to dielectric layers. Conclusively, our results show that the surface states of 1DHMMs exist only when the thickness ratio is larger than 0.15. The disappearance of the surface states indicates the topological phase transition of 1DHMMs. Our experimental results will benefit new applications for manipulating light on the surface of hyperbolic metamaterials.

10227-15, Session 3

Quasimode computation in structures including several dispersive materials

Guillaume Demésy, André Nicolet, Frédéric Zolla, Mauricio Garcia-Vergara, Institut Fresnel (France)

We present a new method for the direct computation of the resonances associated with electromagnetic structures including media with highly dispersive permittivities. An important example is the case of metal nanoparticles in the visible light or infrared frequencies. This is a fundamental problem for plasmonic applications.

Computing the eigenfrequencies corresponding to sourceless solutions of an electromagnetic problem (e.g. the harmonic wave equation for the electric field E) are spectral problems. In the presence of dispersionless media, the discretisation of such problems using the Finite Element Method in the harmonic case usually leads to linear generalized (matrix) eigenvalue problems giving resonance frequencies together with the associated eigenfields (the so called quasimodes).

In the case considered here, the permittivity strongly depends on the very frequency that we are trying to determine. A classical way to introduce dispersion is to use Drude, Lorentz or Sellmeier models. All these models are in fact representations of a dispersive permittivity in the form of a rational function of the frequency f, i.e. N(f)/D(f) where N and D are polynomials in f. A direct way to obtain an eigenvalue problem is to multiply the equation by the denominator D(f). In this case, the discretization of the problem will lead to a generalized polynomial eigenvalue problem (of degree higher than 2). Very recent advances in linear algebra algorithms have provided efficient libraries able to directly tackle such problems (e.g. SLEPc).

Nevertheless, the interesting cases may involve several dispersive media. In this case, D(f) is different in each medium and multiplying the equation by all the different D(f) leads to an eigenvalue problem of very high degree that is much more difficult to solve. Therefore, we multiply each region with the local D(f) (and D(f) can be seen as a discontinuous function between the media). In this case, a special treatment has to be applied to the boundaries: the magnetic tangential field has to be introduced as a Lagrange multiplier on such boundaries and used to control the discontinuity introduced by the local D(f) factor.

The practical implementation is performed using Onelab/Gmsh/GetDP open source packages.

The method can be extended to open problems using Perfectly Matched Layers to determine the quasimodes. The method can also be used for periodic structures using Floquet-Bloch theory. In this case, the problem also depends on the parameters derived from the quasi-periodic condition (e.g. associated with the wavevector). The model can deal with problems that are both open and periodic.

We also have developped rational interpolation techniques that provide accurate N(f)/D(f) directly from experimental data and that are suitable for our model.

In this paper, we present 2D models showing the validity of the approach.

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10227-16, Session 3

Spectral features of the Borrmann effect in 1D photonic crystals in the Laue geometry

Vladimir B. Novikov, Boris I. Mantsyzov, Tatiana V. Murzina, M.V. Lomonosov Moscow SU (Russian Federation)

The Borrmann effect is the fundamental effect in X-ray physics. It is a strong increase of the transmission of a perfect crystal when the X-rays satisfy the Bragg diffraction condition, originating from X-rays localization between the atomic planes in that case. In other words, the Borrmann effect manifests itself by smaller field losses as the Bragg diffraction law is attained. Following the trend of the transfer of the X-ray phenomena into the optical spectral range, in this work we experimentally observed and studied the optical analog of the Borrmann effect for the case of one-dimensional photonic crystals (PhCs). The studies are performed in the Laue diffraction scheme when no photonic band gaps appear and the light does not experience diffraction-induced light attenuation.

We studied the samples of PhCs based on porous fused silica. Samples' manufacturing consists of two stages. First, porous silicon PhCs are fabricated by electrochemical etching of p-doped Si (100) wafer. The PhCs consist of alternating layers of two types, of high and low porosity, characterized by different refractive indexes. The second stage consists in annealing of the crystals in a muffle at 750o C. Depending on the oxidation time, we obtained the PhCs that are partially or fully annealed. The PhCs produced by both techniques have periodical modulation of refractive indexes and losses. Optical losses in the two types of PhCs are different; in partially annealed PhCs (PhC-I) high refractive index layers absorb light due to the presence of residual silicon, while in fully annealed structures (PhC-II) the losses are determined by light scattering in

layers with high porosity (low refractive index layers). PhCs have several hundreds of layers that allow study the effect in the Laue scheme of diffraction.

Optical experimental setup is based on a CW laser operating at the wavelength of 720-890 nm, its linearly polarized beam is focused by a lens on the PhC input edge of the into a spot of 130 um. The silicon photodiode with a large detection region is placed close to the PhC output edge, so the total transmission is measured, including the beams of all diffraction maxima.

We studied the transmission of the two types of PhCs as a function of the angle of incidence of the radiation. We observe that the transmission of the PhC-I samples demonstrates sharp peaks, corresponding to the Bragg angles of diffraction. The appearance of these peaks manifests of the Borrmann effect due to the predominant localization of the optical field in the PhC layers with low absorption. At the same time, the PhC-II structures demonstrate nearly monotonic decreasing of transmission as a function of the angle of incidence. So the effect is different for the structures with light losses in high or low refractive index layers. Spectral dependence of the effect shows a number of peculiarities: alternating appearance and disappearance of total transmission maxima and a strong angular narrowing of maxima for definite wavelengths. Interrelation of the observed effects with degeneracies of the PhC band structure is confirmed by theoretical calculations.

10227-36, Session PS

Plasmonic scattering nanostructures for efficient light trapping in flat CZTS solar cells

Omar A. M. Abdelraouf, Nageh K. Allam, The American Univ. in Cairo (Egypt); Mohamed Ismail Abdelrahaman, Aix-Marseille Univ. (France)

CZTS (Cu2ZnSnS4) is a promising absorbing layer in photovoltaic devices, due to it is low cost, abundancy, and non-toxicity. However, recent developments in CZTS solar cells showed efficiency reaching barely over 9%. The low efficiency of CZTS solar cells is the main obstacle for replacing conventional high cost bulk silicon photovoltaic with CZTS solar cells.

Herein, we propose an alternative route for enhancing the efficiency of CZTS solar cells by using plasmonic scattering nanostructures on the top surface of the CZTS active layer. Metamaterial and plasmonic nanostructures can confine, absorb, guide or scatter incident light in the nanoscale. Each one of these phenomena totally depends on the material type, shape, and geometrical dimensions of the used nanostructures. Therefore, theoretical study of different shapes and materials can guide the highest performance of desired phenomena.

In this work, we studied the effect of changing plasmonic metal nanopyramids' height, periodicity, and tapering angle on light scattering inside active layer of the CZTS solar cells. By sweeping pyramid's height from 100nm to 300nm, periodicity of closed nanopyramids from 100nm to 180nm, and using pyramid base length 25nm, 50nm, 75nm, we found good enhancements in light absorption inside the active layer over reference planar CZTS structures.

The results showed that tapering angle of nanopyramids is a critical parameters in enhancing performance. Using pyramid base length 25nm and 75nm showed highest absorption enhancement of 101.2% and 102.7%, respectively. Using 50nm pyramid base length showed 106.1% light absorption enhancement, 105.3% generation rate enhancement, and 106.3% overall efficiency enhancement compared to simulated reference planar CZTS structure. In all simulations, the highest performance occurred at pyramid's length 300nm and periodicity of 180nm.

Each plasmonic CZTS solar cell structure is designed and analyzed using there dimensional (3D) finite element method (FEM) simulations. Using periodic boundary condition for simulating a smaller cell, and with mesh size is ten times smaller than lowest simulated wavelength. Input port energy came from air mass 1.5 sun light over wavelength range from 300nm to 800nm. Also, we studied effect of replacing molybdenum with refractory plasmonics titanium nitride (TiN). TiN is a promising plasmonic material as it has a similar plasmonic properties to gold at visible wavelength. After using TiN, we found also enhancements in light absorption. These interesting results could open a new way of integrating plasmonic scattering nanostructure inside flat CZTS solar cell for higher efficiency.

10227-37, Session PS

Ferroelectric lithographic microscale assembly of a noble metal nanoparticles applied as a single molecule sensor

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Active plasmonic nanomaterials are an attractive materials in a variety of device applications ranging from solar cells to optical sensors. An important aspect of optimising plasmonic nanomaterials for, e.g., optical sensor applications is the ability to engineer areas of intense, localised electromagnetic fields. Here, the formation of microscale arrays structure from Au nanoparticles using a ferroelectric lithography methodology is demonstrated and the resulting array applied to both surface enhanced Raman scattering and fluorescence detection and imaging.

Ferroelectric lithography via proton exchange-based method was applied to direct self-assembly of Au nanoparticles created by photodeposition on a periodically proton exchanged lithium niobate (PPELN) crystal. The PPELN template affords the ability to tailor the electrostatic fields near the surface of a lithium niobate crystal, which is suitable for driving bottom-up assembly and nano-deposition to engineer the formation of the patterned Au nanostructures (Au-PPELN). This biocompatibile Au-PPELN substrate provides a platform for ultra-sensitive Raman spectroscopy at the single molecule level detection limit. Temporal and spectral acquisitions of localised blinking events have been recorded individually using high-speed detectors and a high-resolution spectrometer, respectively. The acquired spectra indicate that the observed blinking can be assigned to single molecules. This finding opens opportunities to use Au-PPELN as a powerful substrates in the field of ultrasensitive chemical and biochemical analytics.

10227-38, Session PS

Photonic band gap and defect states calculation of 2D octagonal structures

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Photonic crystals are capable of prohibiting certain frequency ranged electromagnetic (EM) waves from propagating in a structured media. The non-allowed frequency range is called photonic band gaps (PBGs) and are analogous to the electronic band gaps resulting from periodic electrostatic potentials in crystals. The radiation with the wavelength of those frequencies in the frequency gap cannot propagate inside these repetitive composites. Plane Wave Expansion (PWE) method is used to form and calculate the band gap and the field patterns of the dielectric rods of the crystal structure [1]. PWE method is combined with the supercell technique so a required size of supercells can be constructed to define the crystal structure with introduced defect states [2]. Using large supercells can be useful for the calculations of the localized defect modes.

The crystal structure is defined as a basic cubic lattice. Then a primitive cell is constructed with four identical atoms, which are placed around a central point at an equal distance with 90 degree between each atom's positions. This central point is assumed to be the lattice point of the cubic structure so the position dependent periodic dielectric function is redefined due to these rod points. The repetition of this unit cell constructs an octagonal crystal structure and the band gap calculations and density of states (DOS) are calculated for the GaAs rods in air and air rods in GaAs background. A defect point is defined at the central point of the constructed octagon and this additional defect enlarges the band gap width tremendously.

Topics: Photonic Crystal, Plane Wave Expansion, Octagon, Photonic Band

Gap, Defect States

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10227-40, Session PS

Complex dielectric films acting as external diffractive 3D photonic crystals to improve Blue OLEDs

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Blue OLEDs are essential to fabricate efficient full color displays, but have a relatively low efficiency. Indeed, the produced light turns out to be strongly coupled to the optical modes of the metallo-dielectric stack waveguide, and tend to remain inside the medium of high optical index. This total internal reflection effect that occurs both in conventional planar bottom-emitting organic and inorganic light emitting devices is responsible for the low outcoupling efficiency – Typically 20% of the electrogenerated photons are coupled to free space. To extract more light, several methods have been proposed, from the internal structuration of the organic layers, to the addition of an external diffractive layer made of micro-lenses or disordered structures.

Internal structuration of the OLED yields high improvements of the external quantum efficiency, but is complicate and costly to set up. We will present low cost techniques that can be easily scaled up to large surface OLEDs. These later uses dielectric films made either with the Langmuir-Blodgett technique [1], either using Breath Figure techniques [2]. We measured an improvement up to 40% of the EQE for a blue OLED emitting at 480 nm.

Besides, we will present a numerical model of this three-dimensional optical OLED cavity. This later extends the well-known one-dimensional formalism that is commonly used to model OLED stacks. It permits to link simply the electrical properties (exciton distribution) to the optical gain in an OLED caped with 3D photonic crystal, what enables global optimisation of 3D-OLED architectures. Eventually, we derive a simple criterion to optimize the photonic crystal shape and size, knowing the architecture of the planar OLED stack.

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10227-41, Session PS

Analytical description of the interaction between light and plasmons: the corrected quasi-normal mode expansion

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Modeling, in nanophotonics, often means running heavy numerical simultations – typically Finite Element Methods, or Finite Difference in Time Domain –, that would compute key physical quantities (absorption and extinction cross sections, Purcell factor), for different excitation parameters (wavelength, polarization, ...).

To overcome this problem, and model efficiently single particles, oligomers, or a complex metasurface, the Quasi – Normal Mode (QNM) expansion seems promising, and has therefore received much attention both in quantum and classical physics in recent years.

Indeed, the QNMs of the device under study need to be computed only once. Then, if excitation is changed (wavelength, polarization, ...) only the expansion coefficients have to be recalculated, and this is done quickly, using an analytic expression even for dispersive and dissipative systems.

In the present work, we derive a corrected QNM expansion that removes the hypothesis of weakly dispersive materials implicitly used in previous works [1]. This leads to more accurate predictions (see Fig. 1). Indeed, an energy correction now appears in the expansion [2] and permits a better description going farther from the pole frequency. In particular, this helps to cure the problem of negative cross section and negative Purcell factor in the infrared range, observed in first works [1]. Note that our formulation remains analytic and has been extended to several QNMs. More precisely, we have set up a rigorous frame, to treat the case where several non-orthogonal QNMs are excited, without using the complex concept of PML integration to deal with their non-orthogonality.

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10227-17, Session 4

Zero index metamaterial for enhanced transmission and beaming *(Invited Paper)*

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Recently, metamaterials with near-zero refractive index have attracted much attention. Light inside these materials experiences no spatial phase change and extremely large phase velocity, makes these peculiar systems applicable for realizing directional emission, tunneling waveguides, large-area single-mode devices and electromagnetic cloaks. In addition, epsilon-near-zero (ENZ) metamaterials can also enhance light transmission through a subwavelength aperture. Impedance-matched all-dielectric zero-index metamaterials which exhibit Dirac cone dispersions at center of the Brillouin zone, have been experimentally demonstrated at microwave regime and optical frequencies for transverse-magnetic (TM) polarization of light. More recently, it has been also proved that these systems can be realized in a miniaturized in-plane geometry useful for integrated photonic applications, i.e. these metamaterials can be integrated with other optical elements, including waveguides, resonators and interferometers.

In this work, using a zero-index metamaterial at the inner and outer sides of a subwavelength aperture, we numerically and experimental study light transmission through and its extraction from the aperture. The metamaterial consists of a combination of two double-layer arrays of scatterers with dissimilar subwavelength dimensions. The metamaterial exhibits zero-index optical response in microwave region. Our numerical investigation shows that the presence of the metamaterial at the inner side of the aperture leads to a considerable increase in the transmission of light through the subwavelength aperture. This enhancement is related to the amplification of the amplitude of the electromagnetic field inside the metamaterial which drastically increases the coupling between free space and the slit. By obtaining the electric field profile of the light passing through the considered NZI/aperture/NZI system at this frequency we found out that in addition to the enhanced transmission there is an excellent beaming of the extracted light from the structure.

We have theoretically and experimentally shown that using a zero-index metamaterial at the inner and outer sides of a metallic subwavelength slit can considerably enhance the transmission of light through the aperture and beam its extraction, respectively.

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10227-18, Session 4

Magnetic Fano-response in toroidal metamaterials

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The static toroidal dipole was predicted by Zeldovich, which appears due to the static currents in atomic nuclei and explain disturbance of parity in the weak interaction. Physically, toroidal dipole is separated element of multipole expansion that corresponds to electrical currents circulating on a surface of gedanken torus along its meridians. Recently, the demonstration of dynamic toroidal dipolar response became possible in metamaterials composed of metamolecules of toroidal topology. Metamaterials with toroidal dipolar response allow to demonstrate a number of special properties such as novel type of EIT, optical activity, extremely strongly localized fields and anapole. We are interested in another property of toroidal metamaterials – magnetic Fano-type response caused by toroidal and magnetic moments in a particular metamolecule. In this paper we demonstrate theoretically and experimentally in microwave at the first time Fano-excitation in toroidal metamaterials. We suggested metamaterials based on a special structure of two types of planar metamolecules separated by dielectric layer.

One of them "Electric" type metamolecule is a planar conductive structure consisting of two symmetric split loops. The incident plane wave excites circular currents along the loops leading to a circulating magnetic moment and, as a result, to a toroidal moment. Moreover, due to the central gap electric moment can be excited in metamolecule. At the same time, destructive/constructive interference between toroidal and electric dipolar moments gives us unique effect as very strong E- field localization inside the central gap and anapole mode.

"Magnetic" type metamolecule is the inverted and rotated variant of the first structure. In contrast to the first case, here we expect very strong localization of magnetic field instead electric field. The magnetic field lines are whirling around the central junction of the metamolecule due to interference between toroidal and magnetic quadrupole moment. Importantly, this configuration allows us to reduce electric moment. Hence, we observe very strong magnetic field localization. Combined together, they support coupled Fano- response with separated strongly concentrated electric and magnetic fields. We discuss this effect and show diamagnetic response due to toroidal Fano-excitation. These metamaterials are promising for magnetic photonics and as Huygens elements.

10227-19, Session 4

Planar toroidal metamaterials: the role of losses, tunability and applications

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Toroidal topology appears in many types of metamaterials, which makes it impossible to describe the electrodynamic properties of such objects correctly without toroidal dipole. Dynamic toroidal dipole is excited by a closed loop of magnetic dipoles, which are caused by electric currents flowing along the meridians of the torus (poloidal currents). One of the most promising cases of toroidal excitation is toroidal excitation in planar metamaterials, which we discuss in this work. We show the peculiar properties of such metamaterials, like extremely high Q-factor and strong electric and magnetic field localization and tunable toroidal metamaterials. Especially we discuss the role of losses in toroidal metamaterials: radiating and non-radiating nature and show that the playing with them can be crucial for effects of high Q-factor applications. We demonstrate experimental characteristics that are in good agreement with modeling results. To prove the toroidal nature of our metamaterial we show the results of multipole expansion that considers toroidal dipole response.

10227-20, Session 4

All-dielectric perforated metamaterials with toroidal dipolar response

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We present metamaterials based on dielectric slab with perforated identical cylindrical clusters with perforated holes, which allow to support the toroidal dipolar response due to Mie-resonances in each hole. Note that proposed metamaterial is technologically simple for fabrication in optical frequency range.

Metamaterial can be fabricated by several methods. For instance, we may apply the molecular beam epitaxy method for deposition of Si or GaAs layers, which have permittivity close to 16. Next step, nanometer/micrometer holes are perforated by focused ion beam method or laser cutting method. Fundamental difference of proposed metamaterial is technological fabrication process. Classically all- dielectric optical metamaterials consist of nano-spheres or nano-discs, which are complicated for fabrication, while our idea and suggested metamaterials are promising prototype of various optical/THz all-dielectic devices as sensor, nano-antennas elements for nanophotonics.

10227-21, Session 4

Optical meta-films of alumina nanowire arrays for solar evaporation and optoelectronic devices

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Nanowires with metallic or dielectric materials have received considerable interest in many research fields for optical and optoelectronic devices. Metal nanowires have been extensively studied due to the high optical and electrical properties and dielectric nanowires are also investigated owing to the multiple scattering of light. In this research, we report optical meta-films of alumina nanowire arrays with nanometer scale diameters by fabrication method of self-aggregate process. The aluminum oxide nanowires are transparent from ultraviolet to near infrared wavelength regions and array structures have strong diffusive light scattering. We integrate those optical properties from the material and structure, and produce efficient an optical haze meta-film which has high transparency and transmission haze at the same time. The film enhances efficiencies of optical devices by applying on complete products, such as organic solar cells and LEDs, because of an expanded optical path length and light trapping in active layers maintaining high transparency. On the other hands, the meta-film also produces solar steam by sputtering metal on the aluminum oxide nanowire arrays. The nanowire array film with metal coating exhibits ultrabroadband light absorption from ultraviolet to mid-infrared range which is caused by nanofocusing of plasmons. The meta-film efficiently produces water steam under the solar light by metal-coated alumina arrays which have high light-to-heat conversion efficiency. The design, fabrication, and evaluation of our light management platforms and their applications of the meta-films will be introduced.

10227-22, Session 5

Liquid-like 2D plasmonic waves *(Invited Paper)*

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We predict some novel 2D plasmonic waves as analogues of corresponding hydrodynamic wave phenomena, including plasmonic splashing and V-shaped ship-wakes excited by a swift electron perpendicularly impacting upon and moving parallel above a graphene monolayer, respectively.

2D plasmons have fueled substantial research efforts in the past few years. Recent studies have identified that 2D plasmons exhibit peculiar

dispersion that is formally analogous to hydrodynamic deep-water-waves on a 2D liquid surface. Logically, many intricate and intriguing hydrodynamic wave phenomena, such as the splashing stimulated by a droplet or stone impacting a calm liquid surface and the V-shaped ship-wakes generated behind a ship when it travels over a water surface, should have counterparts in 2D plasmons, but have not been studied.

We fill this gap by investigating dynamic excitation of graphene plasmons when a monolayer graphene is perpendicularly impacted by a swift electron, as an analogue of hydrodynamic splashing. A central jet-like rise, called “Rayleigh jet” or “Worthington jet” as a hallmark in hydrodynamic splashing, is demonstrated as an excessive concentration of graphene plasmons, followed by plasmonic ripples dispersing like concentric ripples of deep-water waves. This plasmonic jet, serving as a monopole antenna, can generate radiation as analogue of splashing sound. This is also the first discussion on the space-time limitation on surface plasmon generation.

We then demonstrate a V-shaped plasmonic wave pattern when a swift electron moves parallel above a graphene monolayer, as an analogue of hydrodynamic ship-wakes. The plasmonic wake angle is found to be the same with the Kelvin angle and thus insensitive to the electron velocity when the electron velocity is small. However, the wake angle gradually decreases by increasing the electron’s velocity when the electron velocity is large, and thus transits into the Mach angle, being similar to recent development in fluid mechanics.

10227-23, Session 5

Collective dynamics of atoms embedded into negative index materials

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The radiative properties of emitters (e.g. atoms or quantum dots) located close to the interface between two dielectric materials can be significantly modified compared to those in vacuum. The modification results from the presence of surface EM modes known as plasmon guided (PG) field [1,2]. A new category of materials has been proposed, so-called meta-materials [3,4], characterized by specifically designed geometrical structures which drastically modify the density of the EM modes, so the field propagation, also yielding to the PG field [5]. Owing to the high local density of modes, emitters may interact strongly with the surface field which affects their radiative properties. For example, when quantum dots are placed at a distance about several tens of nanometers above two dimensional metal surface, strong coupling could be generated between the quantum dots reflected in the presence of the Rabi oscillations [6]. In the structure composed of zero index and left hand materials, maximum quantum interference and a suppression of the atomic decay rate can be achieved between Zeeman levels due to the anisotropy of the EM modes [7].

In this paper, we present an analytical treatment of the dynamics of two independent atoms located close to the interface of two meta-materials, one of a negative permeability and the other of a negative permittivity. We show that surface plasmon polaritons (SPP), nonradiative electromagnetic excitations associated with charge density waves propagating along the interface are generated. Two atoms located close to the interface can excite the SPP. Hence, the interface would behave as a directional guiding plasma field mode propagating in one direction, formally analogy of a plasmonic waveguide [8]. The mathematical approach we adopt here is based on the Green’s function and image methods, and we show that the collective dynamics of the two atoms are completely equivalent to those of a four-atom system [9]. Our focus is on how the plasma field induced at the interface between the materials leads to the collective behavior of the atoms. The results show that significantly different dynamics occur for the resonant and an off-resonant couplings of the plasma field to the atoms. In the case of the resonant coupling, two threshold coupling strengths exist, which distinguish between the non-Markovian and Markovian regimes of the evolution that different time scales of the evolution of the collective effects can be observed. The Markovian regime is characterized by exponentially decaying whereas the non-Markovian regime by sinusoidally oscillating contributions to the evolution of the probability amplitudes. The solutions predict a long distance population transfer and entanglement mediated by the plasma field. In the case of an off-resonant coupling of the atoms to the plasma field, the transfer occurs by exchanging virtual photons which results in the dynamics corresponding to those of two atoms coupled to a common reservoir. In addition, the entanglement is significantly enhanced under the off-resonant coupling.

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10227-24, Session 5

Nonlocal resonances in nanoplasmonics: analysis and simulations

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Traditionally in plasmonics, the most common approach in analyzing the resonant behavior of light interaction with plasmonic nanostructures has been to apply the local-response approximation (LRA), using – depending on the structure complexity and relation between a characteristic dimension and the interacting wavelength – either (quasi)analytic or numerical approaches. Recently, however, as the characteristic dimensions of such structures have scaled down, it has turned out that more complex models based on the nonlocal response (NOR), or even quantum interaction) of free electrons are desirable, in order to explain novel effects (new resonances, blue spectral shifts). Newly emerging approaches describing the complexity of interactions at nanoscale, connected with emerging new physics, are shown and discussed in this contribution, in comparison with the standard LRA. This reasoning has lately started a rapid increase of interest in developing appropriate nonlocal models. This new field is by no means completed; there are, actually, several nonlocal models existing, based on different starting conditions, and predicting phenomena. These are, however, not always consistent and equivalent. In particular, in our studies, we have concentrated on understanding the interaction and developing a simple model capable of predicting the longitudinal nonlocal response based on the linearized hydrodynamic model, applied to simple structures, such as a spherical nanoparticle. Within our model, we have also shown and compared several alternatives within the approach, with respect to inclusion of the current “damping”, (1) standard model (with a possible increased damping constant), (2) with damping in acceleration, and (3) with liquid-viscosity damping. Also, the extension to generalized nonlocal response model is considered. In parallel, as an alternative (and more general) approach, based on our previous rich experience with Fourier modal methods, we have considered and developed the extension of the rigorous coupled wave analysis technique capable of treating nonlocal response numerically, for more general structures.

10227-25, Session 5

Hybrid metal-organic conductive network with plasmonic nanoparticles and fluorene

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For the development of new generation portable electronic devices, the realization of thin and flexible electrodes have a crucial role. Conductive organic systems can address this issue in different ways. Indeed, conductance in organic molecules were studied in different papers starting from seminal papers in last 70's [1] up to recent ones [2]. Among organic species, conduction and electronic characteristics of Fluorene derivatives were studied in different configurations [3,4]. Unfortunately, the conductance of organic materials is limited by charge transport mechanism [5]. Hybrid system with organic conductive compounds covalently linked with metal centres can lead to enhanced conductivity [6].

Here we synthesized gold and silver nanoparticles (AuNPs and AgNPs) stabilized with a fluorene thiolate derivative, namely 9,9-Didodecyl-2,7-bis(acetylthio)fluorene (FL). In the synthesis process the metal nanoparticles (MNPs) size results to be around 5 nm in diameter [7].

When deposited on a planar substrate, the hybrid compound form a regular network of MNPs separated each other by fluorene spacers covalently linked by thiol groups [8].

We deposited the network on substrate with two interdigitated electrodes in order to measure conductive properties (I-V characteristics).

In I-V measurements it results to be that AgNPs based network is 200 times more conductive than AuNPs one. Selective oxidation of AgNPs network close to positive electrodes gives rise to a Schottky diode behavior in the I-V characteristic that could find potential applications in nano-electronics devices.

The fluorescence and extinction spectra of FL-AgNPs and FL-AuNPs where characterised.

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10227-26, Session 5

General rules for incorporating noble metal nanoparticles in organic solar cells

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Over the recent years, the influence of the addition of noble metal nanoparticles (Au, Ag, Al, Cu) into the bulk heterojunction (BHJ) solar cells on their efficiency and light absorption has been excessively studied. However, most of the experimental research in this field deals with randomly selected sizes and concentrations of the nanoparticles, while theoretical research tends to determine the optimum of all parameters, ignoring technological limitations. Furthermore, several research lines focused on compounds with similar chemical structure, and thus similar optical and electric properties. Such approach provides little help when it comes to admixing metallic nanoparticles into new compound families with different properties. Moreover, most theoretical approaches tend to neglect the fact, that nanoparticles have different dispersion relation than bulk material. This has been proven by recent ellipsometric measurements of silver films deposited on germanium wetting layers, where germanium atoms segregate into the silver grain boundaries [1]. Thus, a layer of tightly packed silver nanoparticles (rather than a continuous layer of silver) has an additional Lorentz component in the permittivity [2]. Neglecting this component in calculations may lead to false conclusions.

In this research, we use a Maxwell-Garnet effective medium approach to calculate the effective permittivity of the active layer comprising metallic nanoparticles, then implement the results into the transfer matrix method to calculate the absorption of light in the entire solar cell. We also perform finite-difference time-domain (FDTD) simulations, treating the active layer and metallic inclusions as independent materials. By modifying parameters of the simulations (real and imaginary pats of refractive index of the active layer, thickness of the active layer, concentration of nanoparticles, additional components in the permittivity of the inclusion depending on the size of the nanoparticles) and comparing the absorption coefficients, we create a set of general rules for incorporating noble metal nanoparticles in the active layer. These principles provide optimal material, size spectrum and fill factor for nanoparticle inclusions, for a set of refractive indices and thicknesses of the active layer, which should be designed considering chemical and electric properties of the active layer polymers. Both methods provide similar results, which show that the optimal concentrations for silver are about 3 times greater than those determined without taking into account additional components in the permittivity of the metal.

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10227-27, Session 6

Photonic crystal microchip laser *(Invited Paper)*

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Microchip lasers, being extremely compact and efficient sources of coherent radiation, generally suffer from the low spatial quality of emitted beam. Only at low power emission regimes the Microchip lasers can emit the beams of reasonable spatial quality. Increase of the pump power, or of the pumping area leads to the deterioration of the spatial quality of the beams, and to the reduction of the brightness of the radiation.

We propose and demonstrate experimentally that the use of intracavity Photonic Crystals (PhCs) can substantially improve the spatial quality of the emission. PhCs were recently shown to provide spatial filtering functionality in single pas schemes [1]. Positioning of such PhC filters inside the cavity of Microchip lasers enabled to decrease the divergence of radiation at high power regimes, and to increase the brightness of emitted radiation. Presently we obtained the enhancement of brightness 3 times due intracavity photonic crystal spatial filtering, or, equivalently, we achieved single-transverse-mode emission at 3 times higher powers [2]. The reported results can be improved with advance of fabrication technologies of of PhC filters.

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10227-28, Session 6

All-dielectric slow light nanolaser based on metamaterials

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In recent years, an increasing number of studies have been observed worldwide on metamaterials, which are artificially structured on a scale much smaller than the wavelength of radiation, so that the properties of metamaterials can be described by an effective medium theory. While materials in nature only possess a small part of electromagnetic responses which is theoretically possible, metamaterials exhibit a series of naturally unavailable electromagnetic properties. Those unprecedented properties, including artificial magnetism from non-magnetic materials, positive ? for metals, negative refraction index, etc., render metamaterials a promising candidate for a wide range of applications.

Among those applications, the lasing spaser (surface plasmon amplification by stimulated emission of radiation) is one of the most important applications due to that the spasers promise a faster and smaller nano-scale optical source in the optical region. Nevertheless, the strict requirements for material properties and Ohmic losses from the metallic parts of the devices limit their practical applications of the spasers. Beside the spasers, another kind of nanolasers, based on stopped light in a waveguide, is also demonstrated. However, this so called cavity-free plasmonic nanolaser also encounters some severe problems such as small coupling efficiency and Ohmic losses, which limit its further applications

In order to solve the problems of inevitable Ohmic losses and low coupling efficiency in spasers and cavity-free plasmonic nanolasers, we propose an all-dielectric slow light nanolaser which employs a dielectric metamaterial with negative refraction index and induces the negative Goos-Hänchen effect in the pumping frequency. As a result, positive and negative power flows are generated in the laser structure, forming energy vortexes. The existence of the energy vortexes indicates that the incident light is trapped in the nanolaser, which prolongs the light-matter interaction time and thus enhances the pumping absorption efficiency. Besides, the eigen-mode of the laser structure is excited and serves as a coherent radiation field, endowing the nanolaser a promising small size despite the diffraction limit. Furthermore, a multiple layered GaAs-InGaAs-GaAs quantum well is employed to act as an active material to emit light. With enough gain, the lasing condition is expected to be established.

10227-29, Session 6

Dielectric-only nanolaser induced by Mie resonance

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Surface plasmon amplification by stimulated emission of radiation (SPASER) is an attractive topic in the field of plasmon recently due to the possibility of further shrink down the size of nanolaser in nowaday. The common model of SPASER is usually accomplished by a nanorod gain material, a plasmon supporting metal film beneath the gain material and a dielectric between the abovementioned in order to maintain the oscillation of plasmon. Even though the thickness of dielectric is smaller than the diffraction limit, the whole structure size is still large compared to incident wavelength. Also, there is a drawback of using metal to support plasmon, Ohmic loss when high frequency will snatch lots of energy. In this work, in order to conquer the problem of Ohmic loss of metal, Mie scattering of dielectric is introduced. As we know about Mie theory, both permittivity and size of a particle can scatter different wavelength. When maximum scattering of the particle is achieved, only a narrow range of wavelength will be scattered strongly. In other words, when Mie resonance occurred, an eigenmode of a dielectric particle is excited. Now we replace the particle's material with a gain material, which generate excitons and as quasi-steady states. Furthermore, only the output wavelength whose generating energy is the same as the energy difference of recombination of excitons will remain. With the gain material, the maximum scattering can almost become infinite.

Thus, to achieve this idea, we first use MBE technique to form an InGaAs quntumwell, sandwiched by GaAs. And AlAs served as a sacrificial layer beneath the above mentioned. The reasons for forming a quantumwell structure that less electron and hole pairs are needed to achieve lasing threshold and poses higher quantum efficiency than bulk material. Second, E-beam lithography and RIE define the size of the device because our design only work well under the condition of specific size. Which can check in simulation result of electrical and magnetic coefficient of scattering. Last, we have to peel the device off from its original substrate because GaAs, a high refractive index material will seize the oscillating field inside the device. So, epitaxial lift off (ELO) technique is introduced to transfer the device structure from epitaxial substrate to a low refractive index material. In the result, we suppose that a device in size around 200 nm in cube will emit about 900nm while pumped by external light source.

10227-30, Session 6

Plasma phase separation in bismuth and antimony chalcogenide crystals

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The multiformity and complexity of the dense plasma processes become obvious after the analysis of the diagram (electron density — temperature), based on the comparison of the following four parameters: the thermal De Broglie electronic wavelength, the mean distance between charged particles, the effective interaction length of charged particles, the radius of electrostatic particle shielding. Within oscillation electron model the superconducting crystal AB is considered consisting of two subsystems 2AB=A2+B2. Free electrons couple to lower system energy. For this purpose it is necessary, that electron energy in a local phase ?12 was essentially much less, than one E1, ?2 in an initial phase where ?12 is interaction energy in an initial phase, ?1, ?2 are interaction energy in the local again formed phase, Tc - superconducting phase transition temperature. It is necessary to satisfy condition, ?_1^2≥?_12^2, ?_2^2≥?_12^2. For component A paired electrons are produced only at T=Tc, for component B paired electrons are formed at T>Tc. The superconducting phase transition is performed with the full formation of paired electrons. Correlated paired electrons are formed below the superconducting phase transition temperature Tc. At T=0 all electrons are dependent on each other – coherent or correlated. In high-temperature superconductors spontaneous division into two phases: superconducting and isolating was revealed. Stratification on two phases in superconducting crystals has been confirmed experimentally: neutron graphic, neutron spectral and spectral researches, an electronic and nuclear paramagnetic resonance.

Oscillation parameters of narrow band layered crystals of bismuth selenide and telluride and antimony telluride for one and two oscillations are calculated. The electron oscillation crystal model equations of real ?r and imaginary ??, ??? components of dielectric function, electronic losses L, ?L are resulted, special points of the optical functions ?r, ??, ???, L, ?L for boundary frequencies ? are probed. Ratios of energy balance of `sublattices on the basis of oscillation electronic model are revealed. It is concluded that these crystals at high hydrostatic pressures and low temperatures are turned into superconductors.

10227-31, Session 6

Study of resonant processes in plasmonic nanostructures for sensor applications

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This contribution is focused on the numerical studies of resonant processes in individual plasmonic nanostructures, with the attention particularly given to rectangular nanoparticles and concominant localized surface plasmon resonance processes. Relevant models for the description and anylysis of localized surface plasmon resonance are introduced, in particular: quasistatic approximation, Mie theory and in particular, a generalized (quasi)analytical approach for treating rectangularly shaped nanostructures. The parameters influencing resonant behavior of nanoparticles are analyzed with special interest in morphology and sensor applications.

Results acquired with Lumerical FDTD Solutions software, using finite-difference time-domain simulation method, are shown and discussed. Simulations were mostly performed for selected nanostructures composed of finite rectangular nanowires with square cross-sections. Systematic analysis is made for single nanowires with varying length, parallel couple of nanowires with varying gap (cut -wires) and selected dolmen structures with varying gap between one nanowire transversely located with respect to parallel couple of nanowires (in both in-plane and -out-of-plane arrangements). The dependence of resonant peaks of cross-section spectral behavior (absorption, scattering, extinction) and their tunability via suitable structuring and morphology changes are primarily researched. These studies are then followed with an analysis of the effect of periodic arrangements. The results can be usable with respect to possible sensor applications.

10227-32, Session 7

Magnetic terahertz metamaterials based on dielectric microspheres *(Invited Paper)*

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Dielectric spheres with high permittivity represent a Mie resonance-based metamaterial. Owing to its high far-infrared permittivity and low dielectric losses, TiO2 is a suitable material for the realization of magnetic metamaterials based on micro-resonators for the terahertz (THz) range.

In a previous work, we experimentally demonstrated the magnetic effective response of TiO 2 microspheres dispersed in air, forming nearly a single-layer sample enclosed between two sapphire wafers [1]. Here we embedded the polycrystalline TiO2 microparticles into a polyethylene matrix, which enabled us to prepare a rigid bulk metamaterial with a controllable concentration of microresonators.

TiO2 microspheres with a diameter of a few tens of micrometers were prepared by a bottom up approach. A liquid suspension of TiO2 nanoparticles was first spray-dried producing fragile TiO2 microspheres. These were subsequently sintered in a furnace at 1200° C for two hours, in order to consolidate individually each sphere. The particles show polycrystalline rutile structure with a porosity of 15%. The microspheres were finally sieved and sorted along their diameters in order to obtain a narrow size distribution. They were mixed with polyethylene powder and a pressure of 14 MPa was used to prepare rigid pellets with random spatial distribution of the TiO2 microspheres.

Using finite-difference time-domain simulations, we investigated how the filling fraction and the ratio between the permittivities of the microspheres and the host matrix affect the position and the strength of the magnetic response associated with the lowest Mie mode. We found that a range of negative effective magnetic permeability can be achieved for sufficiently high filling factors and contrasts between the permittivities of the resonators and the embedding medium.

Using time-domain THz spectroscopy we experimentally characterized the response of the realized structures and confirmed the magnetic character of their response. The retrieved spectra of the effective dielectric permittivity and magnetic permeability were analyzed within Mie theory and Maxwell-Garnett effective medium model in a quasi-stationary regime. We found out that the TiO2 microparticles embedded in polyethylene to fabricate the rigid metamaterials were probably elliptical [2].

To provide a better understanding of the electromagnetic behavior we will also show a near-field THz response of both isotropic polycrystalline and anisotropic monocrystalline TiO2 microsphere [3,4]. In the anisotropic case, the microparticles were sintered at 1400° C. The annealing process melted polycrystalline particle clusters into single crystal TiO2 spheres. It resulted in a strong dielectric anisotropy of the spheres since the ordinary and extraordinary permittivities of bulk rutile in the THz range are 80 and 150, respectively. A splitting of the first Mie mode into two orthogonal magnetic dipole modes was then detected.

The discussed examples show a high potential of TiO2 micro-resonators to realize magnetic THz metamaterials, from cheap mechanically stable structures up to anisotropic resonators.

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10227-33, Session 7

Detection of terahertz radiation in metamaterials: giant plasmonic ratchet effect

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The electromagnetic wave impinging on the spatially modulated two-dimensional electron liquid (2DEL) induces a direct current (DC) when the wave amplitude modulated with the same wave vector as the 2DEL but is shifted in phase (the ratchet effect). The recent theory of this phenomenon predicted a dramatic enhancement at the plasmonic resonances and a non-trivial polarization dependence [1]. We will present the results of the numerical simulations using a hydrodynamic model exploring the helicity dependence of the DC current for silicon, InGaAs, and GaN metamaterial structures at cryogenic and room temperatures. In particular we will report on the effect of the DEL viscosity and explore the nonlinear effects at large amplitudes of the helical electromagnetic radiation impinging on the ratchet structures. We will then discuss the applications of the ratchet effect for terahertz metamaterials in order to realize ultra-sensitive terahertz (THz) radiation detectors, modulators, phase shifters, and delay lines with cross sections matching the terahertz wavelength and capable of determining the electromagnetic wave polarization and helicity. To this end, we propose and analyze the four contact ratchet devices capable of registering the two perpendicular components of the electric currents induced by the elliptically or circularly polarized radiation and analyze the load impedance effects in the structures optimized for the ratchet metamaterial THz components. The analysis is based on the hydrodynamic model suitable for the multi-gated semiconductor structures, coupled self-consistently with Poisson's equation for the electric potential. The model accounts for the effects of pressure gradients and 2DEL viscosity. Our numerical solutions are applicable to the wide ranges of electron mobility and terahertz power.

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10227-34, Session 7

Deposition of organic molecules on gold nanoantennas for sensing

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Deposition of organic molecules on gold nanoantennas are reported through chemisorption for sensing in the mid-infrared (mid-IR) spectral range. The specific nanostructures are gold asymmetric-split ring resonators (A-SRRs) based on circular-geometry with two different 'arc' lengths and are deposited on highly transparent zinc selenide (ZnSe) substrates using electron-beam lithography and lift-off. The plasmonic resonant peaks of specific nanostructures were tuned by varying their geometry to match the vibrational responses of the targeted molecules for their enhanced detection. Gold nanostructures are functionalised through chemisorption of octadecanethiol (ODT) in ethanol solution. The molecular vibrational responses were excited using a broadband mid-IR light source and their transmittance spectra were measured at normal incidence using a microscope coupled Fourier Transform Infrared (FTIR) spectroscopy. The experimental results show specific characteristics upon adsorption of organic molecules on the gold A-SRRs surfaces and are supported using FDTD simulation. The adsorption of ODT on nanoplasmonic structures will act as an interfacial platform for a wide range of sensing applications, such as, attachment of proteins and supportive environments for cell-culture.

10227-35, Session 7

Polarization-controlled high-efficiency color filters using Si nanoantennas

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Metasurfaces provide an opportunity to manipulate the amplitude and phase of the electromagnetic waves with ultra-thin elements. They are usually composed of planar 2D array of nano-elements so called nanoantennas which show practical solution for manipulation of light at subwavelength scale, unlike 3D metamaterials can be fabricated with standard lithographic technics at nano-scale level. Many of the prototype devices have already been demonstrated using the concept of metasurfaces which include meta-lens, vortex plates, holography, and color filters. Color filters attract attention of researchers because of their significant advantages over pigment based printing technology such as high contrast, low power, and ultra-high resolution. Recently, a new trend is emerging to use all dielectric based metasurface filters which are much more efficient as compared to plasmonics color filters and also can be easily integrated with existing electronic circuitry. In this work, we propose polarization dependent widely tunable all dielectric color filters whose basic unit is constituted of Si based cross shaped nanoantennas with different arm lengths arranged on the silicon oxide substrate. Each arm of the nanoantenna responds for different state of polarization of incoming light. We optimize the geometry of the cross shaped nanoantennas by manipulating width and length of arms and numerically demonstrate a wide tunability of the filters in a visible spectrum. The proposed metasurface can be easily integrated with existing electronic circuitry, since it is designed using Si, and allows for obtaining colors in reflection mode which are dependent on the light polarization.

10227-39, Session 7

The coupled NCs based metamaterial for ultra-broadband perfect absorber

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Metamaterials (MMs) have been widely explored for applications, including optics, nanoelectronics, sensing device and absorber. Perfect absorber in visible and near-infrared (NIR) wavelength have stimulated as one of the interesting metamaterial applications because perfect absorbers have a wide range of applications such as energy harvesting, display and etc. However, an achieving a broadband perfect absorber in visible regime still remain a challenge in spite of preceding results from research groups. To date, silver and gold are the most conventional metals applying to metamaterials due to their negative-refractive-index in visible and NIR ranges, and in addition, relatively low loss than other metals. However, the optical properties of these metals cannot be tuned. Nanocrystals based metamaterials have advantages for the controlling of the optical properties when nanocrystals are chemically coupled with a various type and shape unlike silver and gold.

In this study, we focus on the coupled nanocrystals (NCs) for plasmonic and metamaterial perfect absorber in the visible and NIR regions. The coupled NCs were covalently linked via short ligand on surface of each NC in other to control the optical properties of the coupled Ag NCs and the Ag-semiconductors coupled NCs. The coupled NC have the relatively high optical loss compared to gold or silver for application of metamaterial perfect absorber. The various coupled NCs based metamaterial was fabricated by nanoimprint method in other to control plasmoic resonance. Finally, the simulated and fabricated perfect absorber using NC based metamaterials showed the high absorption above 98% in 530-1000nm wavelength and the absorption wavelength could be controlled by coupled NC type and metamaterial structure.

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10228-1, Session 1

Integration of nonlinear and switchable metamaterials with fiber technology *(Invited Paper)*

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No Abstract Available

10228-2, Session 1

Co-sputtered amorphous Ge-Sb-Se thin films: optical properties and structure

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The unique properties of amorphous chalcogenides such as wide transparency in the infrared region, low phonon energy, photosensitivity and high linear and nonlinear refractive index, make them prospective materials for photonics devices[1]. For nonlinear optical properties or optical detection applications, the photosensitivity of chalcogenide materials must be avoided or, conversely, exploited for some others like information storage, photofluidity or post-treatment leading to refractive index uniformity[2-4]. In other words, the important question is whether the chalcogenides are stable enough or how the photosensitivity could be exacerbated for demanded applications. Of this view, the Ge-Sb-Se system is undoubtedly an interesting glassy system given the antinomic behavior of germanium and antimony with respect to photosensitivity. Looking at this glassy system, amorphous films will be found having a different photosensitivity behavior. In order to control and predict the Ge-Sb-Se film photosensitivity, it will be interesting to better understand the involved phenomena. The amorphous Ge–Sb–Se thin films were fabricated by a rf-magnetron co-sputtering technique employing the following cathodes: GeSe2, Sb2Se3 and Ge28Sb12Se60. Radio-frequency sputtering is widely used for film fabrication due to its relative simplicity, easy control, and often stoichiometric material transfer from target to substrate. The advantage of this technique is the ability to explore a wide range of chalcogenide film composition by means of adjusting the contribution of each target. This makes the technique considerably effective for the exploration of properties mentioned above.

In the present work, the influence of the composition determined by energy-dispersive X-ray spectroscopy on the optical properties was studied. Optical bandgap energy E_g^opt was determined using variable angle spectroscopic ellipsometry and UV-Vis-NIR spectrophotometry. The morphology and topography of the selenide sputtered films was studied by scanning electron microscopy and atomic force microscopy. The films structure was determined using Raman scattering spectroscopy. The study of photostructural changes of fabricated films induced by laser radiation with energy close to optical bandgap of the films was maintained under an inert atmosphere to prevent photo-oxidation of exposed films.

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10228-3, Session 1

Determination of Kerr and two-photon absorption coefficients of indandione derivatives

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Due to development of telecommunication industry, optical data transmission systems with all-optical data processing, storage and transmission devices has attracted a great interest. Although concepts for such devices already exist, their implementation is delayed mainly due to difficulties of finding materials with specific third-order non-linear optical (3oNLO) properties. Recently scientist has directed their attention mainly to organic molecules due to their high potential for NLO applications. For organic materials it would significantly contribute to the research if we could define qualitative criteria for molecular structure-3oNLO properties relationship. To extend our knowledge of such qualitative criteria we attempted to analyze 3oNLO parameters of several aminobenziliden-1,3-indandione derivatives to understand how different acceptor and donor groups affects specific 3oNLO properties – Kerr effect and two-photon absorption.

To evaluate 3oNLO properties of our molecules we implemented Z-scan method using picosecound (ps) and nanosecound (ns) Nd:YAG 1064 nm lasers. Measurements were carried out for solutions with organic compounds dissolved in chloroform. While measuring nonlinear refractive index of our materials with ns laser we concluded that thermal effects induced in chloroform can lead to overestimation of Kerr effect magnitude. To evade such error, it is important to choose correct experimental parameters – laser pulse length and frequency. Using ps laser we analyzed Kerr and two-photon absorption effects of organic molecules and compared them with quantum chemical calculations done with Gaussian 09.

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10228-4, Session 1

Investigating nonlinear distortion in the photopolymer materials

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Propagation and diffraction of a light beam through nonlinear materials are effectively compensated by the effect of self-trapping. The laser beam propagating through light-sensitive PVA/AA polymer creates beam divergence, due to higher refractive index, during Self-Written Waveguides (SWWs) formation. In order to investigate this phenomenon, a single light beam is focused on the front surface of a dry photopolymer bulk. The beam self-bending is then examined for parallel beams that was separated by spaces, using array of fiber optic cables. We note that the distance between parallel beams have an effect of changing the refractive indices that eventually diverges or combines the beams. The experimentally verified self-channeling phenomenon was also examined numerically using three-dimension model.

10228-5, Session 2

Nonlinear optics in the mid-infrared: new filamentation physics *(Invited Paper)*

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Recent breakthroughs in ultrafast photonics in the mid-IR help understand complex interactions of high-intensity mid-IR field waveforms with matter, offer new approaches for x-ray generation, enable mid-IR laser filamentation in the atmosphere, facilitate lasing in filaments, give rise to unique regimes of laser-matter interactions, and reveal unexpected properties of materials in the mid-IR range.

10228-6, Session 2

Nonlinearly enhanced linear absorption under filamentation in mid-infrared

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The mid-infrared OPCPA-based laser facilities have recently reached the critical power for self-focusing in air [1]. This ensures the demonstration of the major difference between the mid- and near-infrared filamentation in air: the odd optical harmonics, harshly suppressed by the material dispersion and phase-mismatch in the near-infrared (800 nm), gain reliable energies in the mid-infrared (3.9 μm) filament [1,2].

Another issue that makes mid-infrared filamentation different from the near-infrared one is a lot of molecular vibrational lines belonging to atmospheric constituents and located in the mid-infrared range [3]. As the result the mid-infrared region of interest becomes subdivided into the bands of normal and anomalous dispersion, the former of which leads to the pulse splitting in temporal domain, while the latter produces the confined light bullet.

We simulate the 3.9-μm filamentation using Forward Maxwell equation. We include the tunnel ionization and transient photocurrent as the collapse arresting mechanism, which balances dynamically the instantaneous third-order medium response (similarly to 800-nm filamentation). The key feature that allows us to quantify the losses due to absorption bands is the accurate account of the complex linear absorption index. The absorption index obtained from Mathar model [3] is interpolated to the fine frequency grid (step of about 0.1 THz), and the refractive index is matched according to Kramers-Kro?nig relations [4].

If the initial Gaussian pulse has a center wavelength of 3.9 μm and a duration of 80 fs FWHM, the energy loss in the carbon dioxide (CO_2) absorption band at 4.3 μm is about 1% in the linear propagation regime. But when we take the 80-mJ pulse (about 3 critical powers for self-focusing), the Kerr-induced spectral broadening develops significantly before the clamping level of intensity is reached. In the collimated beam geometry about 2% of the initial pulse energy is absorbed on the CO_2 band before the filament is formed. In the developed filament all the partial losses due to plasma, harmonic generation and absorption on vibrational lines grow up rapidly with the propagation distance, and the absorption on vibrational lines overwhelms all the rest ones. Indeed the new mechanism is revealed – the linear absorption is enhanced by the nonlinear spectral broadening. Thus, the nonlinearly enhanced linear absorption (NELA) is formed. The rotational transitions are estimated to consume as much energy as the free electron generation mechanism [5], which is less than NELA for 3.9-μm filament.

In conclusion, in the 3.9-μm filament the excitations of molecular absorption lines are estimated to provide the major optical losses in the atmosphere as compared with plasma and high-frequency conversion.

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10228-7, Session 2

Optical harmonic generation enhanced due to ultrafast intensity fluctuations

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The effect of the quantum properties of light on nonlinear processes has been well studied theoretically. It has been shown that the efficiency of n-photon nonlinear processes in many cases scales as the normalized n-th order correlation function. For light with high intensity correlation function, the efficiency of the n-th harmonic generation will be considerably higher than for coherent light. The experimental observation of this effect remained difficult until recently, because of the absence of bright sources with strong and fast intensity fluctuations.

For the experimental demonstration of statistical effects in optical harmonic generation we use as a pump the radiation of high-gain parametric down conversion. Such light shows quantum properties (e.g. quadrature or two-mode squeezing) and has large number of photons in one mode. The normalized n-th order correlation function for this light is (2n - 1)!!, which makes it more attractive for nonlinear processes than both coherent and thermal light.

For the generation of optical harmonics we used broadband parametric down conversion around frequency-degeneracy (1600 nm) produced in 1cm BBO crystal from Ti:Sapphire laser (800 nm, 1.6ps, 5kHz, 3W mean intensity). Due to spectral filtering and post-selection technique we could vary the statistics of light from coherent to super-bunched, which allowed us to demonstrate the efficiency enhancement for second-, third-, and fourth-harmonic generation. The obtained experimental results show a good agreement with the theory.

10228-8, Session 2

Forming of supercontinuum in the visible upon filamentation of a femtosecond pulse in the air

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Presently, studies of a supercontinuum (SC) in a visible spectrum range (white light laser) by filamentation of the laser pulses with femtosecond duration in air are a great interest. It is due the availability and great practical significance of this type of radiation for solving tasks in metrology, telecommunications, nanotechnology, optical coherence tomography, remote analysis of the atmosphere, and many others. In this paper we research the conditions of the laser beam filamentation in air and a highly directional SC formation in the visible spectrum range.

A solid-state starter complex “Start 480” was used in the experiments. The complex includes a Ti:Sa master oscillator with a continuous pump

laser, optical stretcher, one regenerative and two multi-pass amplifiers with pulsed pump lasers and compressor on two diffraction gratings. The output radiation parameters were as follows: a central wavelength of 940 nm, spectral width of 26 ± 2 nm (FWHM), pulse duration of 70 ± 3 fs, energy up to 50 mJ, beam diameter of 10 mm. The complex operated with a pulse repetition rate of 10 Hz, and the energy stability was 3%. The output radiation was linearly polarized (horizontally), and the beam quality factor M2 = 2.

Focusing of radiation carried out by a spherical mirror at the different focal length, incidence angles of radiation on the focusing mirror and with a different numerical aperture of focusing system (NA). It is shown that at a low numerical aperture (NA ≤ 1.5?10-3) Kerr nonlinearity plays a decisive role in the formation, existence and termination of the filament. The reasons for the influence of the Kerr nonlinearity are discussed in the report. It is shown that the SC radiation is most stable when formed in the presence of aberrations in the wave front of the laser beam. Optimal aberrations realized at the incidence angle of 150 on focusing spherical mirror with F = 744 mm. Appearance this radiation occurs after visible filament through a gradual conversion of the spectral composition from long wavelength to short wavelength (to 350 nm). On the track section 35–135 cm from the filament, radiation propagates in the form of a spatially stable structure similar to a soliton with a transverse dimension ≤ 300 μm. In this case, SC radiation is significantly different from conical off-axis emission occurring in the aberration-free filament: it has a divergence close to the diffraction limit, linear polarization, and a shorter-range wing of the spectrum. The infrared component of SC has the radiation duration of 25 fs. Research results are presented and forming mechanism of such radiation is discussed.

10228-9, Session 2

Self-trapping of intensities changing under SHG and SWG for high intensive femtosecond laser pulse

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SHG and SFG are used widely in many practical applications such as a substance diagnostics, and imaging of various physical, chemical and biological processes as well as for frequency conversion.

One of very interesting phenomena under the frequency conversion takes place if incident intensity of the basic wave is enough high: a synchronic mode of laser pulses appears under certain conditions. We investigate this phenomenon using the frame-work of long pulse duration approximation and plane wave approximation without applying the basic wave energy non-depletion approximation. Bases on original approach we derive the solution of Schrödinger equations describing the SHG or SWG for femtosecond pulse. Among many modes of SHG we found out analytically the mode corresponding to synchronous intensities changing for interacting waves. We derive conditions of such mode realization in dependence of the problem parameters. After that we verify our analytical consideration using a computer simulation of the problem on the base of the corresponding Schrödinger equations.

10228-10, Session 3

Analysis of THG modes for femtosecond laser pulse

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THG is used nowadays in many practical applications such as a substance diagnostics, and imaging of biological objects and et?. Therefore, understanding of THG features is urgent problem. Below we analyze THG efficiency of a femtosecond laser pulse propagating in a medium with cubic nonlinear response. Consideration is based on computer simulation of the laser pulse propagation with taking into account a self- and cross- modulation of interacting waves. We develop also analytical approach based on using the problem invariant for construction of incident Gaussian pulse evolution along the propagation coordinate. It should be stressed that we did not use a basic wave non-depletion approximation. Nevertheless, we use the frame-work of long pulse duration approximation and plane wave approximation.

Explicit solution of the problem obtained in this frame-work we use for describing of Gaussian pulse propagation. We compare constructed solution of the problem with computer simulation results based on Schrödinger equation. We show that the quantitative agreement between two solutions takes place if the propagation distance is about one dispersion length.

10228-11, Session 3

Nonlinear effects during interaction of femtosecond doughnut-shaped laser pulses with glasses: overcoming intensity clumping

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Interaction of femtosecond laser pulses with bulk glass (fused silica as an example) has been studied numerically based on non-linear Maxwell's equations supplemented by the hydrodynamics-type equations for free electron plasma for the cases of Gaussian linearly-polarized and doughnut-shaped radially-polarized laser beams. For Gaussian pulses focused inside glass (800 nm wavelength, 50 – 100 fs duration, numerical aperture < 0.3), the maxima of laser intensity, free electron density, and absorbed laser energy density do not considerably change with the beam energy (clamping effect). At pulse energies of 200 nJ – 2 ?J, the free electron density in the laser-excited region remains subcritical while the locally absorbed energy density does not exceed ~4000 J/cub. cm. Increasing pulse energy results mainly in increased laser-excited volume.

For doughnut-shaped pulses, the initial high-intensity ring of light shrinks upon focusing. For relatively low beam energies, the internal and external radii of the light ring are decreasing with almost the same rate, creating a subcritical electron plasma of annual spatial distribution. With increasing energy, dynamics of beam focusing can be divided into two stages. At the first stage, the laser beam evolves similarly to the cases of low beam energy and the maximum electron density is similar to that obtained for Gaussian pulses. At the second stage, the light ring splits into two branches, one of which shrinks swiftly toward the beam axis well before the geometrical focus, leading to supercritical free electron density generation. The second branch is the laser light scattered by the electron plasma away from the beam axis, which tends to focus closer to geometrical focus. The near-axis laser-excited volume represents a tube of 0.5–1 μm in radius and 10-15 μm long. The local maximum of absorbed energy can be up to 10 times higher compared to the case of Gaussian beams of the same energy. The tube-like shape of the deposited energy should lead to implosion of material that can be used for improving the direct writing of high-refractive index optical structures inside glass.

Calculated spectra of light transmitted through the sample and scattered to large angles have demonstrated spectral broadening with blue shift. The spectra are considerably different for the two studied pulse shapes that can be used for diagnostics of laser-glass interaction processes.

10228-12, Session 3

Asymmetry of light absorption upon propagation of focused femtosecond laser pulses with spatiotemporal coupling through glass materials

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Ultrashort laser pulses are usually described in terms of temporal and spatial dependences of their electric field, assuming that the spatial dependence is separable from time dependence. However, in most situations this assumption is incorrect as generation of ultrashort pulses and their manipulation lead to couplings between spatial and temporal coordinates resulting in various effects such as pulse front tilt (PFT) and spatial chirp. One of the most interesting spatiotemporal coupling effects is the so-called "lighthouse effect", the phase front rotation with the beam propagation distance [1,2]. The interaction of spatiotemporally coupled laser pulses with transparent materials have interesting peculiarities, such as the effect of nonreciprocal writing, which can be used to facilitate microfabrication of photonic structures inside optical glasses.

In this work, we investigate the influence of these parameters on the distribution of absorbed laser energy inside fused silica glass. The model, which is based on nonlinear Maxwell's equations supplemented by the hydrodynamic equations for free electron plasma, is applied [3]. As three-dimensional solution of such problems would require huge computational resources, a simplified two-dimensional model has been proposed which enables a qualitative insight to a number of PFT effects appearing at volumetric laser modification of transparent materials, including violation of axial symmetry of laser energy absorption and the effect of "quill" writing [4].

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10228-13, Session 3

Modeling the ultrafast electron dynamics upon femtosecond laser-irradiation silicon: transient plasmonics, current generation, and subsequent matter modification

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During the last decades, femtosecond laser irradiation of materials has led to the emergence of various applications based on laser functionalization of surfaces at nano- and microscale. Via inducing periodic modifications on material surfaces (band-gap modification, nanostructure formation, crystallization or amorphization), structural, optical and mechanical properties can be tailored, that makes femtosecond laser processing to be a key technology for nanophotonics, bionanoengineering, and nanomechanical applications. Recently, time-resolved studies demonstrated a transient excitation of non-linear currents on surfaces of band-gap materials laser-irradiated in modification regimes [1], that is seemingly linked with a transient excitation of surface plasmon polaritons [2,3].

Although modification of semiconductor surfaces with femtosecond laser pulses has been studied for more than two decades, dynamics of coupling of intense laser light with excited matter remains poorly understood. During the laser irradiation, a swift generation of a transient over-dense electron-hole plasma dynamically modifies optical properties in the material surface layer. This is accompanied by formation of large gradients of charge-carrier density and must result in ultrafast charge-carrier transport (in particular, surface current generation), transient excitation of surface plasmon polaritons [2,3], and a modification of the laser light propagation [4].

In this work, the electron dynamics upon femtosecond laser excitation of a semiconductor material are studied theoretically on the example of silicon. A model based of the rate and energy balance equations has been developed which takes into account ambipolar diffusion effects, temperature-induced convection flows, surface-induced currents, and thermally/non-thermally melting processes. A special attention is paid to the electron-hole pair dynamics and accurate description of the dynamics of optical response. Modeling data are in agreement with pump-probe reflectivity measurements available in literature.

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10228-14, Session 3

Spectral narrowing in gases using femtosecond laser pulses

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Filamentation in gases due to high power femtosecond pulses results from the combined action of the optical Kerr effect (giving rise to self-focusing) and plasma formation (giving rise to defocusing) that confines optical energy in a small region over a distance longer than the Rayleigh range. Since the discovery of N2 as a potential gain medium, which subsequently led to the formation of nitrogen lasers, it has held a keen interest due to its potential in achieving lasing by remote excitation.

Recently, Yamanouchi and coworkers demonstrated lasing action in N2 in the forward as well the backward directions along the femtosecond pulse propagation. In the present work, we have focused on excitation of N2+ (corresponding to the 391 nm spectral feature) and have measured spectral narrowing. We have investigated the influence exerted by the incident pulse power and gas pressure for incident pulses of durations 40 fs and 10 fs in forward and backward detection modes. Spectral narrowing that occurs for N2 gas at 391 nm shows a dependence on the incident pulse duration. Pressure threshold for different incident powers for lasing has been established. Increase in the signal intensity on varying the incident power is ascribed to amplified spontaneous emission (ASE). White-light-seeded lasing in N2+ is generated by a Ti:sapphire femtosecond laser for different focusing.The lasing lines peak over the trail of the incident broadband spectra.

10228-15, Session 4

Multimodal nonlinear nanophotonics
(Invited Paper)

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Nonlinear nanophotonics is a rapidly developing field of research with many potential applications for the design of nonlinear nanoantennas, light sources, nanolasers, and ultrafast miniature metadevices. A tight confinement of the local electromagnetic fields in resonant photonic nanostructures can boost nonlinear optical effects, thus offering versatile opportunities for the subwavelength control of light. To achieve the desired functionalities, it is essential to gain flexible control over the near- and far-field properties of nanostructures. To engineer nonlinear scattering from resonant nanoscale elements, both modal and multipolar control of the nonlinear response are widely exploited for enhancing the near-field interaction and optimizing the radiation directionality. Motivated by the recent progress of all-dielectric nanophotonics, where the electric and magnetic multipolar contributions may become comparable, here we review the advances in the recently emerged field of multipolar nonlinear nanophotonics, starting from earlier relevant studies of metallic and metal–dielectric structures supporting localized plasmonic resonances to then discussing the latest results for all-dielectric nanostructures driven by Mie-type multipolar resonances and optically induced magnetic response. These recent developments suggest intriguing opportunities for a design of nonlinear subwavelength light sources with reconfigurable radiation characteristics and engineering large effective optical nonlinearities at the nanoscale, which could have important implications for novel nonlinear photonic devices operating beyond the diffraction limit.

10228-16, Session 4

Highly directional second-harmonic generation from AlGaAs nanoparticles

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For a number of years, nonlinear nanophotonics studied metallic nanostructures with intrinsically high nonlinearity. However, due to their Ohmic losses and low heat resistance they cannot be practically applied in nonlinear optical processes for optical frequency conversion. On the other hand, dielectric and semiconductor nanomaterials can overcome these problems since their optical losses at visible and near-IR wavelengths are almost negligible. Such nanoparticles can support both electric and magnetic Mie-type resonances enabling multipolar and directional scattering of light by optical nanoantennas. This capability has triggered a great interest to the study of enhanced harmonic generation by resonant nanoparticles, driven by the possibility to achieve higher frequency conversion efficiencies and to shape the radiation patterns directing them into desired directions. Silicon and Germanium nanoparticles have been first explored due to their large third-order nonlinear susceptibilities [1,2]. However, exploiting materials with second-order susceptibilities, such as GaAs and AlGaAs, would intrinsically increase the conversion efficiency due to the lower-order nonlinearity. Second harmonic generation (SHG) efficiencies exceeding 10-5 have been recently measured in backward direction from AlGaAs [3] and GaAs [4] sitting on an oxide layer. However, because of many challenges in realizing III-V semiconductor nanostructures placed on low-refractive index substrates its fabrication has been avoided, blocking the possibility to explore the SHG directionality in both forward and backward direction.

Here we demonstrate, for the first time to our knowledge, experimental measurements of the radiation patterns of SHG from AlGaAs nanostructures [5]. The nanostructures were fabricated by implementing an epitaxial growth in conjunction with a bonding procedure to a glass substrate. Our final sample contains high quality Al0.2Ga0.8As nanodisks on a glass substrate. The novel configuration allows not only to achieve strong linear resonances and control their spectral position, but also to characterize both forward and backward SHG signals excited by a pulsed laser beam at 1556 nm wavelength and average power of ~1mW. By using back focal plane (BFP) imaging, we measured a SHG radiation pattern vanishing in the direction normal to the disks. This is reflected in the doughnut shape of BFP images due to the quadrupole second harmonic radiation. Also, we observe polarization shaping of the nonlinear signal emitted, where nearly-perfect radial polarization is formed in the forward direction. Last but not least, we demonstrate an unprecedented SHG conversion efficiency of 10-4 [6]. Our results open a novel way for applications of subwavelength nanophotonics to nonlinear spectroscopy of chemical and biological species.

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10228-17, Session 4

Low power symmetry breaking and improved figure of merit for metamaterial nonlinear plasmonic waveguides

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Using plasmonics as a part of nonlinear structures has been seen as a promising approach to boost the nonlinearity because of the strong light confinement achieved. Several nonlinear plasmonic waveguides have already been studied. Among them, nonlinear plasmonic slot waveguides (NPSWs) made of a nonlinear isotropic core of Kerr-type sandwiched between two semi-infinite metal claddings have received a great attention due to the very strong light confinement and to the possible functional controls one can add to it. In addition, the NPSWs have characteristic cross sections approximately 20 times smaller than those of all-dielectric nonlinear waveguides, enabling small footprint photonic devices. One of the key properties of the symmetric NPSWs is the spatial symmetry breaking induced by the nonlinearity. Nevertheless, the experimental observation of such symmetry breaking is still lacking due to the too high needed power. Furthermore, no clear enhancement of the figure of merit of the nonlinear effects in NPSWs has been observed yet due to the high losses.

In this study, we propose and model new symmetric NPSWs made of anisotropic metamaterials either in the positive Kerr-type nonlinear core or in the surrounding claddings. We developed specific methods including FEM based ones in order to compute the nonlinear stationary solutions that propagate in these anisotropic NPSWs. The metamaterials we consider are obtained from simple and realistic stack of bulk layers for a use at the telecommunication wavelength.

For metamaterial cores, the used nonlinear materials are chalcogenide glasses and epsilon-near-zero (ENZ) materials like indium tin oxyde. We choose chalcogenides not only for their high nonlinear coefficient and compatibility with other dielectrics like silica, silicon, or with metals like gold or silver but also for their low two-photon absorption at the telecommunication wavelength. First, we demonstrate that for the isotropic nonlinear cores with bulk ENZ permittivity, the bifurcation threshold of the asymmetric mode is not reduced, as it is usually expected from ENZ properties, but it is increased from GW/m2 threshold to 100 GW/m2. Second, when a realistic diagonal elliptical permittivity with highly anisotropic components including a transverse ENZ one is considered for the nonlinear core, the bifurcation threshold is now reduced around the 10 MW/m2 limit, gaining more than two orders of magnitude compared to the simple NPSWs. This property indicates a strong enhancement of the effective nonlinearity. Furthermore, the slope of the dispersion curve of the asymmetric mode remains positive suggesting a stable mode.

Finally, we consider an isotropic positive Kerr-type nonlinear core (chalcogenide glass) with metamaterial claddings (made of low index dielectric like silica or MgF2 layers with silver ones). We have found that, with well-chosen effective parameters based on the analysis of the guiding properties of the full structure, we obtain a reduction of the bifurcation threshold of the asymmetric mode. More importantly for low power applications, we also get a significant increase of the practical figure of merit of these improved plasmonic waveguides around the telecommunication wavelength compared to the simple NPSWs and to all-dielectric waveguides, even when the losses are taken into account. Consequently, the metamaterial nonlinear waveguides we proposed and studied represent a more compact and more efficient solution for nonlinear integrated optics than the state of the art nonlinear all-dielectric waveguides.

10228-18, Session 4

Nonlinear optical effects in organic microstructures

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Organic microstructures attract much attention as they can provide a number of unique properties while keeping high values of optical nonlinearity and possibility for a relatively easy control over their shape. Such structures allow to change continuously the chemical composition of the substituting medium and to modify continuously their molecular structure and the molecular arrangement within a medium. In this work we discuss the linear optical and second order nonlinear-optical effects in organic microstructures composed by self-assembling technique and formed randomly on top of a solid substrate. They are made from red dye molecules, which possess a non-centrosymmetric structure and thus are perspective for the observation of the second order nonlinear-optical effects. Due to the composition procedure, during the evaporation of the solvent the dye is organized as an ensemble of truncated cones. The bottom (closer to the substrate) diameter of a typical frustum shaped particle is about 1 micron, while the upper one is twice larger; the height of the frustums is also about a micron.

The array of truncated cones reveals a strong fluorescence (FL) with the maximum placed in the spectral range 600-700 nm. In the nonlinear-optical experiments, the radiation of a femtosecond Ti-sapphire laser at 800 nm wavelength was used. In that case, two-photon absorption leads to the appearance of the FL with the second-order dependence on the fundamental beam intensity. Besides, optical second harmonic generation is observed with much weaker peak intensity as compared to that of the FL. We observe a pronounced spectral dependence of the intensity of the averaged nonlinear optical response on the fundamental wavelength, which is consistent with the absorption spectra of dye. The pronounced effect of the absorption of the dye stems also from the results of the hyper-Rayleigh measurements.

The resonant optical response of a single microparticle is studied by means of the FL and nonlinear-optical (NLO) microscopy. The FL spectrum of an individual truncated cone particle reveals a number of narrow peaks above the wide FL band, that are sensitive to the size of a particle, the characteristic spectral distance between the neighboring strong peaks being about 10-20 nm. These spectral features are associated with the excitation of whispering gallery modes inside the organic particles with high values of the refractive index. The corresponding strong light localization inside the microstructures appears as enhanced fluorescence and NLO response. The NLO microscopy shows that the SHG signal is concentrated closer to the outer side of the particles. The obtained data are supported by the results of the FDTD calculations of the optical field distribution inside the microstructures.

Perspectives of application of such type of organic nonlinear microresonators in optical devices are discussed.

10228-19, Session 4

All-optically tunable EIT-like dielectric metasurfaces hybridized with thin-phase change material layers

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One of the ultimate goals in nowadays photonics is a device that has all-optically tunable properties, low loss in the optical communications range and easy fabrication and implementation of the desired design. Further, the control of the resonant responses with dramatic dispersion can lead to slow-light effects, providing a degree of freedom with unprecedented applications for data control and storage. Dielectric metamaterials can be used to obtain a slow-light response, mimicking electromagnetically induced transparency (EIT). EIT is a quantum destructive interference effect that leads to a pump-induced narrowband transparency window within an absorption line of the probe beam spectrum in an atomic system. In metamaterials, EIT-like response can be obtained as a result of destructive interference between so called bright and dark collective modes. The next challenge is to provide an all-optical tuning of such response.

Here we propose a way to bring together the all-dielectric metamaterials to have EIT-like effects and to optically tune the response by hybridizing them with a layer of a phase change material. Our metamaterial is based on Si nanoresonators that can support EIT-like resonant response; the unit cell consists of a rod, that supports a bright mode electric dipole resonance, and of a square-like ring resonator, that supports a dark mode magnetic resonance. The unit cell pitch is around 1?m, and the other geometric parameters are not critical for fabrication. On the top of the resonators there is a thin layer (around 15nm) of a chalcogenide phase change material, which we will use to tune the optical response. Our choice is Ge2Sb2Te5 (GST), since it has two stable phases at room temperature, namely amorphous and crystalline, between which it can be switched quickly, nonvolatively and reversibly, sustaining a large number of switching cycles. These phases differ in optical properties, while still having moderately low losses in telecom range. Since our hybrid dielectric resonators do not have non-radiative losses of metals around 1.55?m, they can lead to a high-Q factor of the EIT-like response in this range. The starting structure is a common Si on insulator sample which is covered by a thin layer of GST and then patterned according to the optimized design that provides a high contrast ratio of the transmission at 1.55?m. The designed metamaterial provides high transmission EIT-like peak at exactly 1.55?m when the GST layer is in the amorphous state. If we then switch the thin layer of GST to its crystalline phase which has higher losses and refractive index, the EIT-like response is red shifted, bringing the minimal transmission at 1.55?m. GST is highly absorbing in the visible range, therefore the switching can be done by using visible laser to heat the GST surface in order to induce the amorphization/crystallization. We have performed transient thermal simulations to choose the optimal laser power and wavelength, supposing the common pulse duration of 50ns and 100ns for amorphization and crystallization, respectively. We strongly believe that such a new concept could lead to great improvements in all-optical photonics.

10228-20, Session 4

Second harmonic generation on self-assembled GaAs/Au nanowires with thickness gradient

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Gallium arsenide (GaAs) nanostructures have attracted a lot of interest for the realization of optical devices such as emitting diodes, nanolasers, nano-elements for integrated solar cells. Among different possible applications, as others materials with the same wurtzite symmetry, GaAs nano-elements can be used as second harmonic generation (SHG) emitters. Efficient coupling of GaAs emitters with plasmonic gold antennas has been recently investigated [1]. A proper coupling with metal plasmonic modes can enhance the local electro-magnetic field in the GaAs nano-element, thus increasing the SHG efficiency.

Here we investigated the SH generation at the wavelength of 400 nm (pump laser at 800 nm, 120 fs pulses) of a "metasurface" composed by an alternation of GaAs nano-grooves and Au nanowires capping portions of flat GaAs. The nano-grooves depth and the Au nanowires thickness gradually vary across the sample. The samples are obtained by ion bombardment at glancing angle on a 150 nm Au mask evaporated on a GaAs plane wafer. The irradiation process erodes anisotropically the surface, creating Au nanowires and, at high ion dose, grooves in the underlying GaAs substrate (pattern transfer). The SHG measurements are performed for different pump linear polarization angle at different positions on the "metasurface" in order to explore the regions with optimal conditions for SHG efficiency. The pump polarization angle is scanned by rotating a half-wave retarder plate. While the output SH signal is analyzed by setting the polarizer in 's' or 'p' configuration in front of the detector. The SH signal collected in reflection is isolated from the reflected pump at 800 nm by using a series of short pass filters and band pass filters centered around 400 nm.

We realized two samples obtained with different argon exposition times. The overall results, integrated also with linear reflectance spectra, show that a trade-off between scattering losses and field confined effect can lead to optimum SHG efficiency.

The best polarization condition for SHG is obtained in the configuration where the pump and second harmonic fields are both 'p' polarized, and the experiments show a SH polarization dependence of the same symmetry of bulk GaAs. Thus, the presence of gold contributes only as field localization effect, but do not contributes directly as SH generator.

We further investigated the samples by studying linear optical properties such as anomalous reflection induced by the generalized Snell's law [2]. These studies confirm the presence of the gradient in the geometrical features of the nanowires.

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10228-21, Session 4

Ultrafast hyperspectral absorption spectroscopy of 2D crystals

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We employ hyperspectral ultrafast transient absorption spectroscopy to investigate charge carrier dynamics in the novel class of two dimensional materials (Graphene and Transition Metal Dichalcogenides)

In our technique the samples are optically "pumped" using the femtosecond tunable pulse coming from an Optical Parametric Amplifier, and "probed" for changes in transmission with a "white light" laser-generated supercontinuum.

Graphene carrier dynamics present a broadband differential absorption with two characteristic lifetimes (hundreds fs and few picosecond) due carrier-carrier scattering and phonon assisted recombination mechanisms. This behavior does not change substantially with the pump energy demonstrating strong carrier-carrier interaction.

Among other Transition metal dichalcogenides we report on the carrier dynamics of few layers of MoS_2. Our results show the presence of negative differential response (bleach) corresponding to the A and B exciton. Measured lifetimes are on the order of tens of picosecond and depends on the pump fluence as well as on the number of layers. We compare the results with a characterization of the time-resolved photoluminescence measured by means of optical Kerr gating.

These results provide insights into the photophysics of these materials and are useful in view of their applications in optoelectronic devices.

10228-22, Session 5

Thermal optical nonlinearity in photonic crystal fibers filled with nematic liquid crystals doped with gold nanoparticles

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Recent advances in microfluidics and nanophotonics have led to a newly emerging field known as optofluidics, which in a complementary way combines two distinct scientific fields such as photonics and fluidics. In optofluidic systems, fluids give fine adaptability, mobility, and accessibility to nanoscale photonic devices which otherwise could not be realized using conventional devices. Materials exhibiting strong nonlinear response to incident light play a vital role in the fields of photonics or optoelectronics. Anisotropic materials as liquid crystals (LCs) enhance optical nonlinearity by up to nine orders of magnitude compared to that of isotropic fluids, making LCs suitable for building all-optical devices.. All-optical switches can be made of microstructured fibers filled either with LCs or dye-doped nematic LCs. Also, LCs doped with anisotropic nanoparticles (NPs) exibit specific wavelength-dependent absorption. Consequently, NPs can behave as dispersed nano-heaters that locally modulate refractive indices of LCs through spatial temperature variations improving the nonlinear optical response of the material.

In this work we have investigated the use of gold nanoparticles (GNPs) as a doping material. The size of the GNP metal center was 2 nm with a distribution of 0.2 nm for the samples studied, that was determined by direct TEM imaging and by X-ray scattering of the diluted NP solution. Initially, the research involved comparing properties of both undoped and doped 5CB (nematic LC) by infiltrating micro-holes a photonic crystal fiber (PCF). A supercontinuum light source and a standard PCF LMA 10 No. 01 was used as a host fiber. Both PCF samples were 20 cm long with 2-3 cm long section infiltrated with the LCs. In both cases, a photonic band gap effect was observed and there has been a difference between both spectra of the effective: undoped photonic liquid crystal fiber (PLCF) and GNP-doped PLCF. The spectrum change characterizing the GNPs doped PLCF could be attributed to NPs distorting LC molecules orientation around them.

Additionally, an influence of the 532-nm laser beam on both undoped and 5CB-doped LC cell has been investigated. Both LC mixtures were introduced between glass cells with a proper surface treatment to induce planar (homogenous) texture. LC cells between crossed polarizers was placed and transmission spectrum of a visible light was observed. Preliminary results showed that the transmitted interference spectrum observed under crossed polarizers is red-shifted.

10228-23, Session 5

Route to high-energy dissipative soliton resonance pulse in a dual amplifier figure-of-eight fiber laser

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Multiple applications such as laser micromachining, optical sensors and square-wave clocks require high-energy pulses. The development of high-energy single pulse within passively mode-locked fiber laser has stimulated a great interest in investigating new laser technologies. However, it has been a difficult task to achieve high pulse energies because of limitations imposed by pulse breakup and multiple pulsing that occur from an excess of nonlinear phase shift per roundtrip. In the anomalous dispersion regime, the pulse energy is limited by the soliton area theorem while in normal dispersion regime it is the nonlinear losses coupled with the finite gain bandwidth. To overcome these problems, several techniques have been proposed such as the usage of large mode-area photonic crystal fibers, beam shaping and chirped pulse amplification. Under beam shaping technique, achieving high energy square pulses can be realized by exploiting the dissipative soliton resonance theory where the energy is not limited by the soliton area theorem and it increases proportionally with allows the pulse width to widen linearly.

Dissipative soliton resonance square pulses were experimentally observed in setups consisting on the nonlinear polarization evolution mechanism in normal and anomalous dispersion regimes. It has also been demonstrated in mode-locked figure-of-eight fiber lasers using optical circulators and dual pumping. These results highlighted the fact that the high non-linearity plays an important role in widening the pulse.

In this work, we present a widely adjustable high energy square pulse laser operating in dissipative soliton resonance in a passively mode-locked figure-of-eight fiber configuration using dual Er:Yb co-doped double clad amplifiers. By manually controlling the power of each amplifier, the pulse width can be varied in a range of 360 ns without generating multi-pulsing instabilities. To ensure that DSR would dominate the mode-locking mechanism, we use a 1.5 km standard single-mode fiber in the cavity. At a maximum pumping power, the laser generated square pulses with 416 ns duration and an average output power of about 1.33 W with a repetition frequency of 133 KHz corresponding to a record pulse energy of 10 ?J.

10228-24, Session 5

Bright-dark rogue wave in mode-locked fibre laser

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Rogue waves (RWs) are statistically rare localized waves with high amplitude that suddenly appear and disappear in oceans, water tanks, and optical systems [1]. The investigation of these events in optics, optical rogue waves, is of interest for both fundamental research and applied science. Recently, we have shown that the adjustment of the in-cavity birefringence and pump polarization leads to emerge optical RW events [2-4]. Here, we report the first experimental observation of vector bright-dark RWs in an erbium–doped stretched pulse mode-locked fiber laser. The change of induced in-cavity birefringence provides an opportunity to observe RW events at pump power is a little higher than the lasing threshold. Polarization instabilities in the laser cavity result in the coupling between two orthogonal linearly polarized components leading to the emergence of bright-dark RWs. The observed clusters belongs to the class of slow optical RWs because their lifetime is of order of a thousand of laser cavity roundtrip periods.

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10228-25, Session 5

Rogue waves driven by polarization instabilities in a long ring fiber oscillator

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We present the results of an experimental and theoretical study of the complex nonlinear polarization dynamics leading to rogue wave's emergence. The theoretical model consists of seven coupled non-linear equations and takes in account both orthogonal states of polarizations (SOPs) in the fiber [1, 2]. The model predicts the existence of seven eigenfrequencies in the cavity due to polarization instability near lasing threshold. By adjusting the laser parameters (the power and the SOP of the pump wave and in-cavity birefringence) we can tune some eigenfrequencies from completely different (non-degenerate states) to coinciding (degenerated states). The experiments were performed with a passively self-mode-locked erbium-doped fiber oscillator implemented in a ring configuration and operating near the lasing threshold. The obtained experimental results are in a good correspondence with the theory. Moreover, it was observed that non-degenerate states of oscillator lead to L-shaped probability distribution function (PDF) and true rogue waves (RWs) regime. Meanwhile, a small detuning from partially degenerated case also leads to L-shaped PDF with the tail trespassing RW threshold, but gives periodic patterns of pulses. This regime probably cannot be considered as a true RWs scenario because of high grade of predictability of the patterns. The partial degeneration, in turn, guides to quasi-symmetric distribution rather typical for white noise than for RWs regime.

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10228-26, Session 6

Photoinduced ?(2) for second harmonic generation in stoichiometric silicon nitride waveguides

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Stoichiometric silicon nitride (Si3N4) waveguides, grown via low pressure chemical vapour deposition (LPCVD), are a reliable photonics platform characterized by low loss and a broad transparency range, from the visible to the mid-infrared. Engineering the waveguide dispersion is of special interest since it allows phase-matching of third-order nonlinear optical processes such as four-wave mixing, supercontinuum [1] and frequency comb generation. In the related material SiN, grown with sputtering and PECVD, second order processes have been observed already. Since SiN deposited with these techniques is amorphous and should therefore posses no bulk ?(2), fabrication imperfections such as strained micro-crystalline silicon or at the free nitrogen dangling bonds are seen as the origin [2]. Field enhancement in SiN ring resonators and Bragg gratings have been used to increase the conversion efficiency for SHG to a maximum of 0.14% [3].

Here, we present for the first time experimental evidence of photoinduced ?(2) for SHG in stoichiometric LPCVD-grown Si3N4 waveguides. The waveguides were designed to phase match the horizontally polarized TEM00 mode at 1064 nm with the second order transverse mode TEM02 at 532 nm. A mode-locked laser delivering 6 ps pulses at 1064 nm with a 20 MHz repetition rate was used as pump laser. However, initially, at fixed input pump power, no SHG was observed. Only after longer irradiation, around 1000 s, 532 nm light was observed to grow from below noise to a saturated value, which indicates the presence of a photoinduced ?(2). We obtained a conversion efficiency close to 0.4%, corresponding to 41 μW at 532 nm with 10 mW of IR light measured after the collection lens positioned directly after the waveguide.

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10228-27, Session 6

Implementation of stimulated Raman scattering microscopy for single cell analysis

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In spite of the fact that fluorescent microscopies represent the fundamental pillars upon which the biological imaging is based on, they show some limitations about the quality of the image and its interpretation: large fluorescent molecules or nanomaterials may bias measurement by altering the physical or physiological properties of the system under examination, some structures and/or molecules are reluctant to labelling, as such as lipids, and the dyes suffer from photobleaching. Therefore, it should be taken advantage of microscopy techniques which afford high chemical selectivity of unlabeled living cells, and in addition, implement real time three-dimensional imaging with high spatial resolution and sensitivity. Stimulated Raman scattering (SRS) microscopy provides a good vibrational contrast mechanism. In fact, SRS is free from the nonresonant background: being SRS signal directly heterodyne mixed and amplified by the input beam with the exact same phase, resulting in a zero non-resonant contribution. In addition, SRS exhibits an identical spectrum to the spontaneous Raman, SRS is linearly proportional to the concentration of the analyte, and it allows straightforward quantification. Therefore, it is natural to consider the application of this technique to label-free imaging of quantitative single cell.

In this paper, the implementation of a SRS microscope is described, obtained as a result of the integration of a femtosecond SRS spectroscopic setup with an inverted research microscope equipped with a scanning unit. Validation tests on images of polystyrene beads are also reported.

SRS microscopy can resolve cellular components within biological systems. It has proven that SRS is particularly powerful for studying lipids. Because of their isolated Raman peaks associated with vibrational states of CH bond (Raman shift 2845cm-1), it is possible to provide a unique signature for lipids inside a cell. For this reason, label-free imaging of lipids droplets inside fixed adipocytes cells is carried out and discussed. Both series of image tests have demonstrated the feasibility of the approach to delineate single cell analysis with chemical specificity.

10228-28, Session 6

Laser-induced periodic surface structure formation: investigation of the effect of nonlinear absorption of laser energy in different materials

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In this work, to get insight into laser-induced periodic surface structures (LIPSS) formation, the relaxation of a modulation in the temperature profile is investigated numerically on surfaces of three different kinds of materials (metals, semiconductor, and dielectrics) upon irradiation by ultrashort laser pulses. The modulation of the temperature is assumed to originate from the interference between the incoming laser pulse and the surface electromagnetic wave, which is considered here as the main mechanism lying at the basis of LIPSS formation [1]. The interference causes the periodic deposition of laser energy into the surface layer of materials, which, in its turn, can trigger periodicities in stress distribution, melting, and ablation, before the final heat dissipation [2,3]. Hence, it is important to investigate the whole route of evolution of laser-irradiated matter from its excitation at ultrashort time scale to the final structure imprinted on material surface.

For comparative studies of the dissipation dynamics of laser energy periodically deposited on the surfaces of materials of different kind (silicon, fused silica, several metals), a simplified 2D model [2] is used. It is based on the two-temperature model (TTM) approach and considers the mechanisms of nonlinear absorption of laser light (multiphoton ionization of different orders and avalanche ionization in band-gap materials; temperature-dependent thermophysical and optical properties in metals) and relaxation (electron trapping into excitonic states in fused silica, Auger recombination in silicon). The TTM is coupled with the Drude model formulation of optical properties of the irradiated materials, considering the evolution of the free-carrier density and/or temperature. For metals, the plasma-like behaviour of the electron population is considered when the electron temperature approaches and exceeds the Fermi temperature [4].

The development and decay of the lattice temperature modulation, which can govern the LIPSS formation, is followed during electron-lattice thermalization time and beyond. It is shown that strong temperature gradients can form along the surfaces of all materials under study within the fluence range of LIPSS formation in experiments. Considerable changes in optical properties of these materials are found as a function of time, including metals, for which a constant reflectivity is usually assumed. The effects of the resulting nonlinear absorption on the surface temperature dynamics are reported.

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10228-30, Session 6

Parametric Raman anti-Stokes laser at 503 nm with phase-matched collinear beam interaction of orthogonally polarized Raman components in calcite under 532 nm 20 ps laser pumping

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Stimulated Raman scattering (SRS) in crystals can be used as a simple and non-expensive solution for the single-pass frequency conversion to the Stokes-shifted wavelengths that are not readily available from solid-state lasers. Anti-Stokes shift of the laser frequency can also be realized using Raman-active media but it needs phase matching condition fulfillment because this is a parametric four-wave mixing process at resonant Raman nonlinearity where two photons of the fundamental laser radiation interacting with one Stokes photon produce one anti-Stokes photon. Therefore the parametric Raman anti-Stokes generation requires not only phase matching, but also biharmonic pumping by two waves having frequency difference equal to the Raman frequency of the Raman-active medium. In the simplest scheme only one pump laser can be used for the parametric Raman laser because the second pump wave can be generated by SRS in the same Raman-active medium. However, practically all the known crystalline parametric Raman anti-Stokes lasers have very low conversion efficiencies of about 1 % at theoretically predicted values of up to 40 %. This can be explained by that these lasers are based on non-collinear phase matching of four-wave mixing

for compensation of dispersion wave mismatch, but the non-collinear phase matching has narrow angular tolerance in comparison with angular divergence of the interacted beams.

In our investigation, to widen the angular tolerance of four-wave mixing and to obtain high conversion efficiency into the anti-Stokes wave we propose and study a new scheme of the parametric Raman anti-Stokes laser at 503 nm with phase-matched collinear beam interaction of orthogonally polarized Raman components in calcite under 532 nm 20 ps laser pumping. We use only one 532-nm laser source to pump the Raman-active calcite crystal oriented at the phase matched angle for orthogonally polarized Raman components four-wave mixing. Additionally, we split the 532-nm laser radiation into the orthogonally polarized components (pumping ordinary wave and probing extraordinary wave) entering to the Raman-active calcite crystal at the certain incidence angles to fulfill the nearly collinear phase matching and also to compensate walk-off of extraordinary waves for collinear beam interaction in the crystal with the widest angular tolerance of four-wave mixing.

Several configurations and two calcite crystals (21 or 32 mm long) were investigated. The initial results demonstrate that 1 uJ of anti-Stokes 503 nm component was generated with the efficiency of 5% from probe beam and 2% overall efficiency from pump and probe beams altogether. Higher efficiency from the probe beam more than 20% can be achieved for lower anti-Stokes energy of ~300 nJ. To the best of our knowledge this is the highest conversion efficiency into the anti-Stokes wave in comparison with the known crystalline parametric Raman anti-Stokes lasers.

10228-31, Session 6

Numerical simulation and comparison of nonlinear self-focusing based on iteration and ray tracing

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Self-focusing phenomenon is observed in nonlinear materials owing to the interaction between laser and matter when laser beam propagates. Some of numerical simulation strategies such as the beam propagation method (BPM) based on nonlinear Schrödinger equation and ray tracing method based on Fermat's principle have applied to simulate the self-focusing process. In this paper we present an iteration nonlinear ray tracing method to simulate the self-focusing phenomenon. The nonlinear material is also cut into massive slices just like the existing approaches, but instead of paraxial approximation and split-step Fourier transform, a large quantity of sampled real rays are traced step by step through the system with changing refractive index and laser intensity by iteration. At first the sampled rays are generated with intensity of light or energy factors. Then the rays are traced using different algorithm according to the materials that the rays transmit through. For linear materials, we use the classical ray tracing method to calculate the rays one by one. For nonlinear materials, all of the incident rays must be traced slice by slice so as to use the iteration algorithm to determine the laser intensity distribution and the nonlinear refractive index field at the same position. Because of the limited ray sampling, the quantization errors appear. So a smooth treatment is employed in this process to correct the laser intensity distribution at each slice for managing the error caused by the under-sampling. When the rays propagate out of the nonlinear materials, classical ray tracing is available again. The characteristics of this method is that the nonlinear refractive indices of the points on current slice are calculated by iteration so as to solve the problem of unknown parameters in the material caused by the causal relationship between laser intensity and nonlinear refractive index. As shown by the examples and comparison that the simulation data of this algorithm such as the first self-focusing point is coincident well with the exiting simulation methods, and the efficiency and accuracy are improved. The method presented is developed based on the ray equation called Lagrangian description of Fermat's principle, and is more suitable for engineering application with lower time complexity, and has the calculation capacity for numerical simulation of self-focusing process in the systems including both of linear and nonlinear optical materials. At the end of the paper, the advantages and disadvantages of this algorithm are discussed.

10228-32, Session 6

Graphene quantum dots with nitrogen-doped content dependence for highly efficient dual-modality photodynamic antimicrobial therapy and bioimaging

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Reactive oxygen species is the main contributor to photodynamic therapy. The results of this study show that a nitrogen-doped graphene quantum dot, serving as a photosensitizer, was capable of generating a higher amount of reactive oxygen species than a nitrogen-free graphene quantum dot in photodynamic therapy when photoexcited for only 3 min of 670 nm laser exposure (0.1 W cm?2), indicating highly improved antimicrobial effects. In addition, we found that higher nitrogen-bonding compositions of graphene quantum dots more efficiently performed photodynamic therapy actions than did the lower compositions that underwent identical treatments. Furthermore, the intrinsically emitted luminescence from nitrogen-doped graphene quantum dots and high photostability simultaneously enabled it to act as a promising contrast probe for tracking and localizing bacteria in biomedical imaging. Thus, the dual modality of nitrogen-doped graphene quantum dots presents possibilities for future clinical applications, and in particular multidrug resistant bacteria.

10228-33, Session 6

All-optical variable-length packet router with contention resolution based on wavelength conversion

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All-Optical Switching (OS) emerges as an attractive approach to implement future power-efficient high-speed optical core routers with greater scalability, high integration capabilities and reduced cost. For all optical packet switching, the principle of operation of different architectures is label processing and packet forwarding. The main used components are a demultiplexer for label extraction, an All-Optical Flip–Flop (AOFF) for label processing and an optical switch for packet forwarding. In most developed architectures optical switches based on Semi-conductor Optical Amplifier Mach-Zehnder Interferometer (SOA-MZI) are the most used.

In previous work, we have proposed an all optical packet forwarding architecture that provides a high bit rate solution to forward optical packets using SOA-MZI [1]. Nevertheless this architecture needs to be improved in order to cope with contention. A novel all optical packet router architecture supporting asynchronous, variable-length and labeled packet is proposed. Wavelength conversion is the adopted contention resolution strategy in this router architecture. Thus we show that the contenting packets are detected and forwarded according First In First Out (FIFO) strategy with a different wavelength. Optisystem simulations are realized and error-free functionality is achieved for different bit rates.

This router architecture with wavelength conversion contention resolution relies on combining packets detection. It need only the result of AOFFs and optical AND gates responses to operate with any packet length and at high bit rate.

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10228-34, Session PS

Significant improvement in the thermal annealing process of optical resonators

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Thermal annealing performed during process improves the quality of the roughness of optical resonators reducing stresses at the periphery of their surface thus allowing higher Q-factors [1-5]. After a preliminary realization reported in [6], the design of the oven and the electronic method were significantly improved thanks to nichrome resistant alloy wires and chopped basalt fibers for thermal isolation during the annealing process. Q-factors can then be improved with a factor of five.

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10228-35, Session PS

Multi-objective optimization of coupled device based on optical fiber with crystalline and integrated resonators

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Because of the advantages in terms of reproducibility for optical resonators on chip which are designed of various topologies and integration with optical devices. To increase the Q-factor from the lower rang [10^4 - 10^6] to higher one [10^8 -10^10] [1, 2] one use crystalline resonators. It is much complicated to couple an optical signal from a tapered fiber to crystalline resonator than from a defined ridge to a resonator designed on a chip. In this work, we will focus on the multi-criteria optimization of the crystalline resonators under thermal finite element analysis (based on COMSOL multi-physic software) [3- 5] and subject also to technological constraints of manufacturing. The coupling problem at the Nano scale makes our optimizations problem more dynamics in term of design space.

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10228-36, Session PS

2W@318.6nm single-frequency cw UV laser system via single-pass SFG followed by cavity-enhanced SHG

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The long-range dipole-dipole interaction between neighboring Rydberg atoms may yield the Rydberg blockade effect, which is a promising way to realize two-atom entanglement and to implement C-NOT two-qubit gate. If choosing a single-step excitation to a desired atomic Rydberg state, the decoherence arising from the population of intermediate state can be avoided. For exciting cesium atoms from ground state (6S_1/2) to nP_3/2 (n = 70 ~ 100) Rydberg state via single-photon transition, we have implemented a high-power single-frequency cw 318.6nm UV laser system by single-pass sum-frequency generation (SFG) from two infrared lasers to 637.2nm followed by cavity-enhanced second-harmonic generation (SHG). Based on the well-developed Er-doped and Yb-doped fiber lasers and fiber amplifiers, as well as efficient laser frequency conversion technology with periodically-poled nonlinear crystals, more than 8.7W@637.2nm single-frequency red laser output has been achieved by single-pass SFG of two fiber-amplifier-boosted infrared fiber lasers at 1560.5 nm and 1076.9nm with a 40-mm-long PPMgO:LN crystal, and corresponding conversion efficiency is ~38%. The output red laser beam has good power stability and excellent beam quality. Then, followed by four-mirror-ring-cavity enhanced SHG with a Brewster-angle-cut BBO crystal, more than 2.2W@318.6nm single-frequency UV laser output has been achieved with 4.0W incident red light. The output UV laser beam can be continuously tuned over 4GHz, and the typical root-mean-square (rms) power fluctuation is less than 0.87% over 30 minutes. The line-width of the UV light is estimated to be less than 10kHz. The beam quality factors, M^2(X) and M^2(Y), are measured to be ~ 1.16 and ~ 1.48 respectively. This 318.6nm UV laser system provides a solid foundation for the subsequent single-step 6S_1/2 - nP_3/2 (n = 70 ~ 100) Rydberg excitation of cesium atoms. References: [1] J. Opt. Soc. Am. B, Vol.33 (2016) p.2020; [2] Opt. Commun., Vol. 370 (2016) p.150

10228-37, Session PS

Tunneling current emission spectrum of biased impurity in the presence of electron-phonon interaction

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We performed theoretical investigations of the tunneling current noise spectra through single-level impurity in the presence of electron-phonon interaction by means of the non- equilibrium Green function formalism. A fundamental link between quantum noise in tunneling contact and light emission processes was revealed. Tunneling current noise spectra through a single level impurity atom was calculated both in the presence and in the absence of quasi-particle interaction for a finite bias voltage and it was identified as a source of experimentally observed light emission from bias microscopic contacts. Our findings provide important insight into the nature of non-equilibrium electronic transport in tunneling junctions with electron-phonon interaction.

We carefully studied total tunneling current noise spectra directly connected with phonon assisted emission processes. We demonstrated that the edge of tunneling current noise spectra in the presence of electron–phonon interaction is displaced on the value of phonon frequency in comparison with the case when electron–phonon interaction is neglected, consequently spectra cut off occurs at higher frequencies. We showed that, in the presence of electron–phonon coupling in addition to the resonant peculiarity associated with the single level of the quantum dot, additional peculiarities with the separation set by the frequency of phonon mode appear.

Our approach can be generalized to more complicated systems and gives possibility for a better understanding of the effect of electron–phonon interaction on light emission and quantum noise in atomic and molecular tunneling contacts.

10228-38, Session PS

Dynamic photonic crystals dimensionality tuning by laser beams polarization changing

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Photonic crystals properties [the presence of photonic band gap, refractive index (dielectric constant) modulation on a length scale close to the wavelength and strong light localization] are very attractive for numerous devices fabrication, such as zero-threshold lasers, low power optical switchers, memory elements and devices for high-capacity data storing. A dynamic photonic crystal is one in which the property of the crystal is modulated while a photon pulse is inside the crystal. Now a days the small refractive index modulations that are required to create dynamic photonic crystals are readily achievable in standard optoelectronic systems. So, the use of dynamic photonic crystal structures may provide a unifying platform for diverse optical information processing tasks in the future.

We demonstrated a simple way to create dynamic photonic crystals with different lattice symmetry by interference of non-coplanar laser beams in colloidal solution of quantum dots. With the proposed technique we have made micro-periodic dynamic semiconductor structure with strong nonlinear changing of refraction and absorption and analyzed the self-diffraction processes of two, three and four non-coplanar laser beams at the dynamic photonic crystal (diffraction grating) with hexagonal lattice structure.

To reach the best uniform contrast of the structure under investigation and for better understanding of the problems, specially raised by the interference of multiple laser beams we have also performed theoretical calculation of the periodic intensity field in the QDs solution.

We demonstrated that dynamic photonic crystal structure and even dimension can be easily tuned with a high speed by the laser beams polarization variation without changing of experimental setup geometry. This means that polarization strongly influences the optical properties of dynamic photonic structures.

10228-39, Session PS

Interplay between convection and bistability in a pattern forming system

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A conventional laser beam propagating through a nonlinear medium may become unstable against modulation instability. Under peculiar conditions, one may observe the appearance of correlated satellite beams called pattern. For its potential application in optical memories, spontaneous pattern formation has been investigated in a large variety of nonlinear optical systems [1-3]. One of the generic features of the pattern- forming systems is the subcritical bifurcation from which the instabilities originate [4]. The bifurcation being subcritical, the pattern branch coexists with the homogeneous solution within a given range of the system parameters [5].

Recent preliminary work from our group in an optical system composed of a bulk photorefractive crystal subjected to a single optical feedback [6] has shown the possibility to increase the bistability between pattern and homogeneous solutions by playing with the misalignment of the feedback mirror: the bistability area becomes larger with respect to larger mirror misalignments.

In the current paper, we unveil the origin of this observation and the underlying physical mechanisms. Especially, we demonstrate the role of the convection in the bifurcation scenario. We show the interplay between drift induced instabilities and bistability.

Moreover, an external background illumination applied onto the nonlinear medium is used as a external parameter for controlling the size of the bistability. We question the role of this parameter and demonstrate how the background illumination makes the bistability area even larger.

It is worth mentioning that such observations are interesting in the framework of cavity solitons. One of the crucial mechanisms for the existence of such localized intensity peaks is the presence of an optical bistability between a stable Turing pattern and a homogeneous steady state. Therefore being able to control the range of parameters where cavity solitons may exist is the key for their generation in nonlinear optical systems.

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10228-40, Session PS

Smooth spectral broadening in single-mode fiber

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In the last decade, Yb-doped crystals have been highly investigated to generate ultrashort, high average power pulses. Due to the good thermal and spectral properties of such crystals, Yb-doped solid state lasers became widely used in academic and industrial applications. On the other hand, while conventional oscillators generates few hundreds of femtoseconds (200 fs to 400 fs) only a few matrices can produce sub 50 fs pulses [1].

Post-compression techniques in optical waveguides (silica fiber, hollow-core fiber) are attractive methods with many advantages to reduce the duration of the above mentioned sources. These fibers provide an extended medium to enhance nonlinear effects, as well as the good transvers mode quality. Efficient post-compression of Yb-doped oscillator generated pulses have been demonstrated in fiber-based systems [2]. Substantial spectral broadening was achieved by Self-Phase Modulation (SPM), however it generates widely modulated spectrum, leading to pulses with low contrast after recompression. Efforts have been made, using parabolic pulse profile or electro-optic phase modulator [3,4], to compensate the modulation caused by SPM.

Here we investigate theoretically and experimentally the non-linear pulse propagation in a single-mode fiber with a non-negligible degree of biregringence. In fact, the potential two orthogonal polarization component propagating in the fiber result in additional nonlinear effects such as Cross-Phase Modulation (XPM) and Nonlinear Elliptical Polarization Rotation (NER). The numerical simulation is based on the coupled Nonlinear Schrödinger Equations. The theoretical model contains the effect of SPM, XPM, group velocity mismatch and second order dispersion as well. Impact of polarization and average power of the input pulse was also investigated. We show that with polarization control, the combination of the above mentioned nonlinear effects can generate a broad, unmodulated spectrum leading to very short pulses with high temporal quality. The simulation results are in good agreement with the experimental observations.

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10228-41, Session PS

Photo-induced nonlinear absorption in carbon nanostructures

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Photoinduced nonlinear absorption of a new form of fullerene-conformable nanostructures – the astralens and three types of carbon nanoclusters was investigated. The astralens represents polyhedral multi-shell toroidal carbon nanoparticles a typical dimensions about 150 nm. They have optical strength and thermal stability more than fullerenes, and they have high chemical stability. The astralens are not soluble in any solvent, but they form a stable suspension.

Nonlinear absorption of astralens aqueous suspension and three types of carbon nanoclusters was investigated by the method of z-scanning using the Nd3+-glass laser at 1064 nm in Q-switching and short-term resonant modulation of losses regimes. In the Q-switching regime the pulsewidth was 50 ns. In the regime of the short-term resonant modulation of losses the pulsewidth was about 2 ns. The radiation intensity was changed from 105 W/cm2 to 1011 W/cm2. It was found that at the laser radiation intensity about 107 W/cm2, the absorption coefficient increases sharply. The increase of the absorption coefficient for different nanoparticles was observed at different values of laser radiation intensity. The dependence of the absorption coefficient from the intensity of transmitted laser radiation and the reached maximum value of the absorption coefficient is also different for the investigated nanoparticles.

The observed nonlinear absorption may be caused by the effect of reverse saturable absorption. A numerical model of the propagation of laser radiation in a medium with reverse saturable absorption was created. Because the investigated nanoparticles have a size of more than 100 nm, their energy structure is well described by band theory. In the numerical model, the medium is described by three equations for populations of the ground and two excited states. Comparison of experimental results with numerical simulations showed that the nonlinear absorption in the investigated nanoparticles is associated with the mechanism of reverse saturable absorption. The effectiveness of this mechanism is determined by two parameters – the relaxation time of the first excited state and the ratio of the absorption cross-section ground and first excited states. It was shown that the differences in the absorption nonlinearity of the investigated types of carbon nanoparticles is determined by the difference of these parameters. Relaxation times and the ratio of absorption cross-section for the researched types of carbon nanoparticles determined by the numerical simulation.

10228-42, Session PS

Poling dynamics of an EO active material using parallel-plate electrodes

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Development of active photonic components requires materials that can display the desired properties as well as offer easy bulk processing if ever to be considered for commercial use. Electro-optic (EO) materials are very promising for active component development. The EO effect has been displayed in liquid and inorganic crystals. A third group of non-centrosymmetric materials with these desired properties are organic molecules (chromophores) imbedded in a polymer matrix. This group of EO materials can display a wide range of desired properties such as high Pockels coefficients (r33), low dielectric permittivity and most importantly – easy processing.

For organic EO polymers to display their nonlinear properties macroscopically, the material must be poled. The poling procedure consists of applying an electrical field and heating the polymer matrix to its glass transition temperature, which allows the chromophores to collocate according to the field applied. Once the material is cooled back to room temperature, the chromophore molecules stay aligned and macroscopic nonlinear properties in the material can be observed.

Poling is one of the main contributing factors of efficiency in organic EO materials. A stronger applied field contributes to a higher order parameter in the material and it can better display macroscopic nonlinearity. A higher chromophore concentration also provides a higher EO coefficient. However, local electrical fields of molecules in short distances can interact and hamper the alignment of molecules in the applied field therefore lowering the efficiency.

In this work we review our experimental efforts of describing poling dynamics of an organic chromophore imbedded into a polymer matrix, as well as the influence of chromophore concentration on material properties by measuring second harmonic generation in sandwich type samples with parallel electrodes. The experimental data are compared to theoretical models developed in the laboratory.

10228-43, Session PS

Measuring dispersion in nonlinear crystals beyond detectors' spectral range

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Single-photon sources are essential for the experimental implementation of various quantum information processing and communication protocols. One of the most popular types of such sources is based on spontaneous parametric down-conversion (SPDC). In this phenomenon, which occurs in a crystal with large effective nonlinearity, some photons, from the so-called pump pulse, are converted into pairs of signal and idler photons. Thanks to this, one may obtain photons, which are correlated in many degrees of freedom. Their wavelengths strongly depend on the crystal's properties, such as poling period, refractive index, temperature, or more generally phase-matching conditions. By carefully chosing the aforementioned parameters it can be possible to generate pairs of photons with significantly different wavelengths (e.g. one belonging to the visible range, and the other one to the IR spectra range).

In this work we show a simple technique for dispersion measurements in a nonlinear crystals by making use of phase matching in the process of parametric down-conversion itself. The method can be applied for various types of crystals, in which spectrally non-degenerated phase-matching conditions are satisfied. It also allows to determine the coefficients of Sellmeier equations with limited detection capabilities, caused by the lack of detectors specified for desired spectral range.

Here we use an exemplary PPKTP crystal, phase matched for 396 nm to 532 nm and 1550 nm in order to demonstrate our method. The phase matching conditions can be tuned by changing the temperature of the crystal and the pump wavelength. We collect a selection of spectra for the pump beam and one of the resulting SPDC photons as a function of the temperature and pump beam wavelength. This allows us to generate respective tuning curves, which we fit the model to. As a result a precise dispersion relations (Sellmeier equations) can be obtained in a very broad wavelength range even outside the detection range of the measurement apparatus.

10228-44, Session PS

Generation of intensive surface plasmon polariton pulses due to the induced modulation instability effect

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The evolution of intensive surface plasmon polariton (SPP) waves in a dielectric-metal-dielectric structure is investigated taking into account absorption properties of metal in the optical range. It is shown that some spatial harmonic perturbations of the SPP wave can be unstable due to the nonlinear optical properties of silver film. Under the influence of the modulation instability effect the initially weak perturbations grow quickly in time leading to spatial redistribution and longitudinal localization of SPP wave energy on the subwavelength scale. Thus, the traveling SPP wave is transformed into a train of subpicosecond pulses. In the case of the film thickness of 5 nm, the pulsation frequency equals 4.6 THz, the duration of each pulse is less than 0.1 ps. For the film thickness of 10 nm the temporal dynamics at any given point looks like separated pulses of longer duration 0.5 ps attributed to a smaller group velocity of SPP. In this case the repetition rate of the pulse train is about 1.4 THz. Numerical simulations show that the modulation gain coefficient is sufficient large to provide the modulation instability effect in plasmonic structure with losses at the initial period (up to 5-10 ps) after the SPPs excitation when the impact of attenuation is weaker than the nonlinearity. The demonstrated results allow us to conclude that the layer structure comprising a conductive film of subwavelength thickness opens the way to solving many challenging optoelectronics tasks, like generating signals with a repetition rate in the terahertz range and ultrafast trains of subpicosecond optical pulses.

10228-45, Session PS

Generation of wide spectrum and pedestal-free pulse compression in highly nonlinear dispersion increasing fiber

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The optical pulse evolution in a highly nonlinear normal dispersion increasing fiber has been considered both experimentally and theoretically. The numerical simulation and experimental results allow to derive that the use of highly nonlinear fiber with the normal group velocity dispersion (GVD) increasing from zero to the value of about 10 ps^2/km provides a rational compromise between pre-compression spectrum broadening of average power pulse in fibers with a low and high normal GVD. Instabilities arising due to self-phase modulation in the fiber with a low normal GVD impair the pulse envelope and disturb the chirp. In another case, a high GVD leads to rapid pulse broadening with low chirp. In both cases, the quality of pulse compression is rather poor. A fiber with increasing normal GVD enables pulses with high chirp rate that is nearly constant along the pulse width.

The experimental results demonstrate that the use of highly nonlinear normal dispersion increasing fiber enables spectrum broadening of picosecond pulses up to 40 nm. Demonstration of pedestal-free pulse compression in a standard single-mode fiber below 200 fs indicates the strong linearity of the chirp superimposed onto the pulse. The pulse compression is enhanced for higher peak power of the input pulse. The proposed scheme for pre-compression pulse spectrum broadening can be effectively used to compensate an asymmetric spectral dependence of the fiber dispersion and avoid nonlinear wave-breaking instabilities. The longitudinal fiber profile providing the most efficient pulse compression for the given dispersion spectral dependence should be further optimized.

10228-46, Session PS

Modulation instability of wave packets propagating in inhomogeneous nonlinear fiber

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The formation conditions and the effective gain of frequency-modulated soliton wave packets in a non-uniform along the length of active optical fibers were investigated. For packets modulated wave propagating in the nonlinear dependence of the fibers with the dispersion of the fiber length, the power of the generated pulses can be considerably increased in comparison with the homogeneous fibers. Due to the constant growth of the spectral width of the generated pulse sequence can no longer return to the state of the modulated continuous wave. As a result, the pulse duration with some fluctuations steadily declining. The amplitude and period of these oscillations are also reduced.

10228-47, Session PS

The impact of dispersion of the ultrashort light pulses on the THz radiation formation from asymmetric air plasmas

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The terahertz radiation from asymmetric air plasmas receive great attention recently, because of its potential use in all air terahertz spectrometers. In this scheme, the second-harmonic field of a femtosecond laser field is combined with its fundamental, which accelerates charges of air plasma produced by the focused laser pulses. This process ultimately emits an intense and THz pulse with very broad frequency spectrum. The dispersion of the short light pulses plays an important role the quality and the quantity of terahertz radiation produced. The goal of this study is to understand better the role of this dispersion on terahertz radiation from asymmetric plasmas.

The light source consists of a multipass Ti:sapphire amplifier system able to produce sub-20 fs laser pulses with 1.2 mJ pulse energy at 200 Hz repetition rate and 800 nm central frequency. The terahertz radiation detected by electro-optic sampling with the help of a nonlinear ZnTe crystal. The dispersion of the light pulses is controlled by a programmable

acousto-optical filter (Fastlite Dazzler).

Our key findings are that the dispersion of light has significant impact on the terahertz amplitude as a function of GDD and the spectral content of the terahertz pulse can be controlled through the dispersion of the fundamental pulse. The terahertz amplitude shows interesting oscillation as a function of GDD with a periodicity of approximately 1000 fs2. It has been found that the oscillation is not related to the amount of plasma generated, but is proportional to the asymmetry of the electric present in the plasma.

Numerical simulations are performed similar to the one presented by Kim et al. [1], which considered transform limited pulses for both SH and fundamental pulses. However, the group delay mismatch in a relatively thick (>100 μm) BBO crystal stretches the SH pulses significantly. THz field generation is more optimal when the fundamental pulse is stretched as well to match the SH pulse, instead of being transform limited. The relative phase between the fundamental and SH fields greatly impacts the THz signal, which was already shown in [1]. This phase changes with the dispersion tuning and creates oscillation, which we experienced experimentally. The simulations and experiments are in reasonable agreement.

In conclusion, it has been shown that the dispersion has interesting impact on the terahertz radiation producing strong oscillations as function of GDD. A key observation is that the maximum terahertz intensity is found away from the transform-limited duration of the fundamental pulse, which has been the result of the group-delay mismatch of the fundamental and second harmonic light pulse through the type 1 BBO crystal. The next step in this work to further explore the dispersion at higher order and to investigate the impact of dispersion on the frequency composition of the terahertz radiation.

10228-48, Session PS

Creation technique and nonlinear optics of dynamic one-dimensional photonic crystals in colloidal solution of quantum dots

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Dynamic photonic crystal have provoked great interest because of the possibility to use it for researching non-stationary processes in different materials, as well as creating on its basis optoelectronic devices. One-dimensional dynamic photonic crystals was formed by a periodic spatial modulation of dielectric permittivity induced by the two ultrashort laser pulses interference in semiconductor quantum dots CdSe/ZnS (QDs) colloidal solution intersecting at angle ?. Dynamic band gap of one-dimensional photonic crystal theoretically predicted to be formed for an arbitrarily small difference in the dielectric constants. Pseudo-localization is realizable for small refractive index ratio of two dielectric media, and in this case, the band gap is called the stop-band. Formation of stop band wavelength ?_(st-b) depends on the angle of intersection of the laser beams ? by the formula: ?_(st-b)=(?_ex n)/(sin ?/2) (where n – refractive index, ?ex – laser wavelength).

The fundamental differences of dynamic photonic crystals from static one which determine the properties of these transient structures are the following. I. Dynamic photonic crystals lifetimes determined by the nature of nonlinear changes of dielectric permittivity. II. The refractive index change is determined by the intensity of the induced standing wave maxima and nonlinear susceptibility of the sample.

We use the pump and probe method to create the dynamic one-dimensional photonic crystal and the analysis of its features. Two focused laser beams with a wavelength ?_pump =532 nm (second harmonic) are the pump beams, that form in the colloidal solution of quantum dots dynamic one-dimensional photonic crystal. The picosecond continuum, generated by the first harmonic of laser (1064 nm) in heavy water, is used as the probe beam. The self-diffraction of pumping beams on induced by them dynamic one-dimensional photonic crystal indicates about spatial combining of beams.

In the case of the resonant excitation of the exciton transition in QD CdSe/ZnS besides of the two beams passed through the cell with colloidal QDs holding the direction of the input beams propagation, beams propagating along the of the cones surface, the tops of which are located in the volume of the induced dynamic photonic crystal (with the section plane of the screen - hyperbole) were discovered. The Gaussian intensity distribution of laser beams leads to periodic dynamic structure formation and decreasing dielectric permittivity modulation to the beams periphery. The beams forming dynamic structure in colloidal CdSe/ZnS QDs “feel” its boundaries (the size of the formed dynamic photonic crystal less than beam square) and self-diffract in the directions defined by the condition (k_diff-k_0)?=m (beams diffraction Laue condition at a chain of atoms), where k_0 is the wave vector of the incident beam, k_diff is the wave vector of the diffracted beam, ?=(?_ex)/(2sin ?/2) - period of dynamic one-dimensional photonic crystal). We measured the transmission spectra of dynamic one-dimensional photonic crystal by pump and probe method, that allows us to analyze wavelength of the stop-band.

10228-49, Session PS

Automatic method for features extraction for images achieved by stimulated Raman scattering microscopy

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The interest in label-free bioimaging has led to the implementation of microscopic techniques based on Coherent Raman Scattering. In particular, Stimulated Raman Scattering (SRS) was studied as an alternative way to provide both the vibrational contrast and the noninvasive characterization of microscopic objects.

On the other hand, computational approaches to bioimaging analysis are recently used to extract quantitative information about both the structure and dynamics of biological systems at the single-cell level.

The basic idea of this paper is to join the potential of vibrational contrast of SRS imaging and the strength of computational approaches to bioimaging analysis, in order to extract quantitative information about both the structure and dynamics of biological systems at the single-cell level. Therefore, quantitative biological imaging for SRS modality can be achieved not only through an optimization of microscopy apparatus but also through an appropriate implementation of image analysis techniques. One of the primary tasks in quantitative features image analysis is the detection of the objects, on which performing the extraction of the features. For this reason, a segmentation process is required to detect discrete areas that represent the objects to analyze. A segmentation process should take into account the intrinsic contrast modality, offering by label free nonlinear optical imaging, in order to perform a correct detection of the objects.

Many of methods, devoted to segmentation of structures inside SRS images, use manual or semi-automatic processes. However, an automatic process for the segmentation is preferable, since the results produced by manual or semi-automatic processes are difficult to reproduce, considering that they depend on the operator, and moreover, the interaction increases the risk of bias in the results.

In the present work a fully automatic method for the segmentation of SRS images is proposed for the segmentation of the subcellular structures inside a SRS image. The method is based on an automatic threshold for the binarization of the image and on an automatic partition of the foreground in the objects of interest. Moreover, some quantitative features are extracted from the detected objects of interest, in order to evaluate the possible morphological changes of an object in the SRS images, acquired changing the vertical axis of objective microscope. The results show that the proposed method can lead to an accurate segmentation of the microstructures inside a single cell.

10228-50, Session PS

TiN Nanoparticles for enhanced THz generation from LT-GaAs-based photoconductive antennas

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Terahertz (THz) technology is a rapidly developing field and several application areas are ideally suited for an implementation of this technology. These applications include spectroscopy, security, material science, monitoring of industrial production processes and plant physiology. THz spectroscopy is mainly based on the use of photoconductive antennas which are driven by ultra-short laser pulses. Low-temperature-grown GaAs (LT-GaAs) is a widely employed material for an excitation wavelength of around 800 nm. Consequently, there have been many attempts to optimize the performance of this material. Furthermore, the impact of the antenna structure has also been studied.

Due to the effect of the surface plasmon resonance, plasmonic nanoparticles (NPs) can localize the light field and therefore enhance significantly the performance of some optoelectronic devices. Here, NPs are employed for an enhanced generation of terahertz radiation from LT-GaAs-based antennas. In this work, we prepared plasmonic TiN NPs by both direct ultrasonication (ULS) and pulsed laser ablation (PLA) techniques. The particle size, Zeta potential, and absorbance are used to characterize the NPs in their colloidal forms. Further, a comparison with commercial Au NPs is made. A layer of poly-dispersed TiN NPs, which had been prepared by PLA and deposited on the surface of an LT-GaAs device, show an improvement of the THz signal generation from coplanar striplines antennas with an enhancement ratio in the range of nearly 100%.

10229-1, Session 1

Energy-efficient superconducting single flux quantum technology for integration with optical circuits *(Invited Paper)*

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Energy-efficiency has become the dominant metric in choosing technologies for implementing the next generation computing systems, enabling scalable quantum computing systems, large cryogenic sensor arrays including superconducting single-photon detector (SSPD) arrays, etc. The progress in these areas will not be possible unless a significant improvement in energy efficiency is achieved over the technologies available today. The heart of the problem is in a relatively low energy-efficiency of current circuit technologies consuming too much energy for readout, processing, storing and moving data between sensor arrays, data or signal processors, memories, computing nodes and cabinets. Superconducting Single Flux Quantum (SFQ) technology by virtue of its inherent low power dissipation, high speed, lossless interconnect present an excellent opportunity to dramatically increase the circuit energy efficiency. Recently, a significant progress has been achieved in increasing energy efficiency of SFQ circuits by introduction of zero-static power SFQ logics including dc-biased energy-efficient RSFQ (ERSFQ and eSFQ) and ac-biased Reciprocal Quantum Logic (RQL) with switching energies less than attoJoule. When combined with a zero-energy ballistic transfer of SFQ pulses over passive transmission lines, the SFQ-type circuits can demonstrate the higher energy-efficiency in complex digital and mixed-signal circuits as compared to any other circuit technologies. Circuit fabrication technology evolves towards combining SFQ circuits with spintronic devices, superconducting detectors including SSPDs, and photonic components such as waveguides paving the way to integrate sensors, readout and processing circuits and optical interfaces onto a single integrated circuit. These developments are fundamentally transforming superconducting electronics to achieve new functionalities and applications.

10229-2, Session 1

Superconducting nanowire single-photon detectors: recent advances *(Invited Paper)*

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Since superconducting nanowire single-photon detectors (SNSPDs) were invented in 2001, researchers have kept improving their performances and have used these detectors in applications including lunar optical communications and experimental quantum optics. This talk reviews recent advances in SNSPDs, with particular emphasis on (1) high-efficiency, polarization-insensitive SNSPDs and (2) timing jitter of SNSPDs.

For high-efficiency, polarization-insensitive SNSPDs, we have designed fractal SNSPDs integrated with metallic nano-antennas that can boost the absorptance of both TE- and TM-polarized incident photons from free space over 80% over a broad spectrum. We have also designed waveguide-integrated SNSPDs that can achieve over 99% absorptance for photons in TE-like and TM-like modes.

For timing jitter of SNSPDs, we have investigated (1) intrinsic timing jitter; (2) noise-induced timing jitter; and (3) an SNSPD integrated with a current reservoir to reduce the timing jitter. After we illustrate the mechanisms of the timing jitter of SNSPDs, we propose, design, and fabricate SNSPDs with reduced timing jitter.

10229-3, Session 1

SNSPD with parallel nanowires *(Invited Paper)*

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Superconducting nanowire single-photon detectors (SNSPDs) have shown to be promising in applications such as quantum communication and computation, quantum optics, imaging, metrology and sensing. They offer the advantages of a low dark count rate, high efficiency, a broadband response, a short time jitter, a high repetition rate, and no need for gated-mode operation. Several SNSPD designs have been proposed in literature. Here, we discuss the so-called parallel nanowires configurations. They were introduced with the aim of improving some SNSPD property like detection efficiency, speed, signal-to-noise ratio, or photon number resolution. Although apparently similar, the various parallel designs are not the same. There is no one design that can improve the mentioned properties all together. In fact, each design presents its own characteristics with specific advantages and drawbacks. In this work, we will discuss the various designs outlining peculiarities and possible improvements.

10229-4, Session 1

Amplitude distributions of dark counts and photon counts in NbN superconducting single-photon detectors integrated with the HEMT readout.

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We present a new operation regime of NbN superconducting single-photon detectors (SSPDs) by integrating them with a low-noise cryogenic high-electron-mobility transistor and a high-load resistor. The integrated sensors are designed to get a better understanding of the origin of dark counts generated by the detector, as our scheme allows us to distinguish the origin of dark pulses from the actual photon pulses in SSPDs. The presented approach is based on a statistical analysis of amplitude distributions of recorded trains of the SSPD photoresponse transients. It also enables to obtain information on energy of the incident photons, as well as demonstrates some photon-number-resolving capability of meander-type SSPDs.

10229-5, Session 2

Position-sensitive CdZnTe detectors with virtual Frisch-grid design for X- and gamma-ray sensors *(Invited Paper)*

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High position resolution CdZnTe (CZT) drift detectors offer unique capabilities for imaging gamma-rays and correcting the response non-uniformities caused by crystal defects. Recently, we proposed to develop an array of position-sensitive CZT drift detectors for making X- and gamma-ray sensors. Here, we will present the results from testing the first prototypes of such arrays. The array prototypes employ 6x6x20 mm3 CZT crystals encapsulated into polyester shells with 4-5 mm-wide charge-sensing pads placed near the anode. The pad signals provide X-Y position information, which allow for more accurate corrections of the charge losses caused by crystal defects. The basic multi-element array (module) consists of 16 detectors grouped into 2x2 sub-arrays, each having a common cathode made by connecting together the cathodes of the individual detectors. The cathode signals provide position information along the Z coordinate. Each module is coupled with its front-end ASIC chip, which captures signals from 16 anodes, 32 pads and 4 cathodes. As we will describe in the talk, this feature significantly improves the performance of detectors fabricated from typical CZT material and, thus, extends their acceptance boundaries, leading to an increase in the yield and an expected decrease in cost. The pulse-height spectra obtained with uncollimated radioactive sources validated the operational principles of such devices, and demonstrated how the sensing pads can be used to compensate for the non-uniformity of response caused by extended defects in CZT crystals. The results presented here indicate strong correlations between individual sensors' responses and the crystal defects revealed by using several material characterization techniques.

10229-6, Session 2

Achieving subpixel resolution with time-correlated transient signals in pixelated CdZnTe gamma-ray sensors using a focused laser beam

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High-resolution position-sensitive detectors have been proposed to correct response non-uniformities in Cadmium Zinc Telluride (CZT) crystals by virtually subdividing the detectors area into small voxels and equalizing responses from each voxel. 3D pixelated detectors coupled with multichannel readout electronics are the most advanced type of CZT devices offering many options in signal processing and enhancing detector performance. One recent innovation proposed for pixelated detectors is to use the induced (transient) signals from neighboring pixels to achieve high sub-pixel position resolution while keeping large pixel sizes. The main hurdle in achieving this goal is the relatively low signal induced on the neighboring pixels because of the electrostatic shielding effect caused by the collecting pixel. In addition, to achieve high position sensitivity one should rely on time-correlated transient signals, which means that digitized output signals must be used. We present the results of our studies to measure the amplitude of the pixel signals so that these can be used to measure positions of the interaction points. This is done with the processing of digitized correlated time signals measured from several adjacent pixels taking into account rise-time and charge-sharing effects. In these measurements we used a focused pulsed laser to generate a 10-micron beam at one milliwatt (650-nm wavelength) over the detector surface while the collecting pixel was moved in cardinal directions. The results include measurements that present the benefits of combining conventional pixel geometry with digital pulse processing for the best approach in achieving sub-pixel position resolution with the pixel dimensions of approximately 2 mm. We also present the sub-pixel resolution measurements at comparable energies from various gamma emitting isotopes.

10229-7, Session 2

(Cd,Mg)Te and (Cd,Mn)Te single crystals for time-resolved detection of x-ray photons

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We report on the practical implementation of (Cd,Mg)Te and (Cd,Mn)Te photoconductive devices as a diagnostic x-ray detection tool. High-energy photons were generated using a multi-terawatt (MTW) laser system, designed for advancing research in the physics of high-energy x-ray and directed-particle beams. The MTW laser is a single-shot, hybrid chirped pulse amplification system that combines optical parametric amplification with neodymium-doped laser-glass amplification to produce compressed output-pulse energies of up to 20 J in a below 1-ps-wide, transform-limited pulse, yielding peak powers in excess of 40 TW and "on-target" intensities of up to 4x1019 W/cm2. As detectors, we used highly resistive (> 109 ?–cm) single-crystal Cd0.92Mg0.08Te and Cd0.9Mn0.1Te materials, grown by a high-pressure, vertical Bridgman method. The 5-mm-size platelets were incorporated into especially designed holders and biased up to 1500 V. We have conducted a series of real-time, nanosecond-level measurements by collecting bursts of broadband x rays emitted by metallic targets, illuminated the MTW pulses. The energy of generated x rays ranged from ~1 keV for the Al target to >100 keV for the Au one. In addition to x rays, we have also detected high-energy protons emitted via target normal sheath acceleration mechanism. Results from our studies showed significant enhancement of the charge collection efficiency for crystals that underwent the post-growth annealing process. Furthermore, we observed a direct relationship between the incident laser energy and the peak voltage response in our detectors.

10229-8, Session 2

Correlation between electrical field distribution and defect levels of CdZnTe and CdZnTeSe radiation detectors

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CdZnTe (CZT) and CdZnTeSe (CZTS) radiation detectors are attractive candidate materials for fabricating room-temperature radiation detectors. The distribution of the internal electrical field within these detectors can substantially affect the transport behavior of electrical charge and, therefore, degrade the photon counting capability and associated device performance. The internal electrical field can be changed by the build-up of space charge, which is closely associated with various types of defect-related levels in the detector crystals. In this work, we use Pockels effect measurements, coupled with external stimulation of light at different wavelengths, to investigate the changes of the internal electric field of CZT and CZTS detectors by exciting various defect levels. These defect levels are also studied using low-temperature photoluminescence spectroscopy. The correlation between the two measurements will be discussed. Our efforts help to better understand and improve the electrical and structural properties of CZT and CZTS for photon-counting applications.

10229-28, Session 2

Front-end ASIC for virtual Frisch-grid cadmium zinc telluride detectors

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Photon detectors rely on front-end application specific integrated circuit (ASIC) to capture the interaction events. Here, we describe a new ASIC developed to readout Virtual Frisch-Grid Cadmium Zinc Telluride (CZT) detectors. Corresponding to each ionizing event in the detector, the ASIC measures the amplitude and timing at the anode, the cathode, and the four sense electrodes associated with each sensor in the detector array. The ASIC is comprised of 52 channels of which there are 4 cathode channels and 48 channels which can be configured as either anode channels with a baseline of 250 mV or sense channels to process bipolar signals with a baseline of 1.1 V. Each channel performs low-noise charge amplification, high-order shaping, peak and timing detection along with analog storage and multiplexing. The ASIC has a footprint of 7.6 x 10 mm2 and dissipated 177 mW of power. With a bar detector module connected and biased, an electronic resolution of ~220 e- rms for charges up to 100 fC in the 3 MeV range was measured. Preliminary bi-parametric data show a resolution of 1.3% FWHM at 662 KeV when a single bar detector was connected and biased to 3 KV at 298K.

10229-9, Session 3

High-performance integrated pick-up circuit for SPAD arrays in time-correlated single photon counting *(Invited Paper)*

Giulia Acconcia, Alessandro Cominelli, Pietro Peronio, Ivan Rech, Massimo Ghioni, Politecnico di Milano (Italy)

The analysis of optical signals by means of Single Photon Avalanche Diodes (SPADs) has been subject to a widespread and steadily increasing interest in recent years, driven by the need for ultimate sensitivity in various scientific and industrial applications such as Fluorescence Lifetime Imaging (FLIM) and Förster Resonance Energy Transfer (FRET) in life sciences, Laser Imaging Detection and Ranging (LIDAR) in remote objects sensing and Quantum Key Distribution (QKD) in cryptography and communication.

In recent years, the development of multichannel high-performance Time Correlated Single Photon Counting (TCSPC) acquisition systems has undergone a fast trend. Concerning the detector, best in class results both in terms of photon detection efficiency (especially at the wavelengths of most interest in medical and biological applications) and dark count rates, even with large active areas, have been obtained resorting to technologies developed on purpose for the fabrication of SPAD detectors, usually referred to as custom technologies. Nevertheless, the engineering of the SPAD electric field used to improve the detector performance came along with a strong dependence of the detector timing jitter from the threshold used to determine the onset of the photogenerated current flow.

In this scenario, the avalanche current pick-up circuit plays a key role in determining the timing performance of the TCSPC acquisition system, especially with a large array of SPAD detectors, where the electrical crosstalk among pixels can have a detrimental effect on the timing accuracy.

We present a new read-out circuit suitable to be the building block of a densely integrated high-performance TCPSC system. The circuit is based on a 2GHz-bandwidth trans-impedance amplifier that is able to collect the SPAD avalanche current while keeping the SPAD anode at a fixed voltage. In this way, it is possible to minimize the interference between adjacent channels when a photon is detected, and thus the crosstalk. Developed in 0.18μm HV technology, the pick-up circuit can provide the information about the photon arrival time with a timing jitter as low as 32ps with a 50μm-diameter custom technology thin SPAD. The circuit is also quite versatile: it can be used with different SPAD detectors, including the new Red Enhanced SPAD.

Starting from these results, we also designed a fully differential version of the pick-up circuit. The main feature of this circuit is that it can be connected to two detectors, where one of the two can be used as dummy cell. In this way, it is possible to reject common mode disturbances with great benefits on the circuit performance. In particular, the fully differential read-out circuit can be used in a fast-gating setup, thus opening the way to the exploitation of this circuit in a larger and larger number of applications. When used in conjunction with a fast active quenching circuit (AQC) connected to the cathode terminal of the SPAD, for example, the differential amplifier is able to filter out the disturbances injected by the AQC, allowing us to provide excellent timing performance (≈45ps) even if the events are close to the beginning of the gate window.

10229-10, Session 3

High-efficiency dynamic routing architecture for the readout of single photon avalanche diode arrays in time-correlated measurements

Alessandro Cominelli, Giulia Acconcia, Pietro Peronio, Ivan Rech, Massimo Ghioni, Politecnico di Milano (Italy)

In recent years, the Time-Correlated Single Photon Counting (TCSPC) technique has gained a prominent role in many fields, where the analysis of extremely fast and faint luminous signals is required. In the life science, for instance, the estimation of fluorescence time-constants with picosecond accuracy has been leading to a deeper insight into many biological processes.

Although the many advantages provided by TCSPC-based techniques, their intrinsically repetitive nature leads to a relatively long acquisition time, especially when time-resolved images are obtained by means of a single detector, along with a scanning point system. In the last decade, TCSPC acquisition systems have been subjected to a fast trend towards the parallelization of many independent channels, in order to speed up the measure. On one hand, some high-performance multi-module systems have been already made commercially available, but high area and power consumption of each module have limited the number of channels to only some units. On the other hand, many compact systems based on Single Photon Avalanche Diodes (SPAD) have been proposed in literature, featuring thousands of independent acquisition chains on a single chip. The integration of both detectors and conversion electronic in the same pixel area, though, has imposed tight constraints on power dissipation and area occupation of the electronics, resulting in a tradeoff with performance, both in terms of differential nonlinearity and timing jitter.

Furthermore, in the ideal case of simultaneous readout of a huge number of channels, the overall data rate can be as high as 100 Gbit/s, which is nowadays too high to be easily processed in real time by a PC.

Typical adopted solutions involve an arbitrary dwell time, followed by a sequential readout of the converters, thus limiting the maximum operating frequency of each channel and impairing the measurement speed, which still lies well below the limit imposed by the saturation of the transfer rate towards the elaboration unit.

We developed a novel readout architecture, starting from a completely different perspective: considering the maximum data rate we can manage with a PC, a limited set of conversion data is selected and transferred to the elaboration unit during each excitation period, in order to take full advantage of the bus bandwidth toward the PC.

In particular, we introduce a smart routing logic, able to dynamically connect a large number of SPAD detectors to a limited set of high-performance external acquisition chains, paving the way for a more efficient use of resources and allowing us to effectively break the tradeoff between integration and performance, which affects the solutions proposed so far.

The routing electronic features a pixelated architecture, while 3D-stacking techniques are exploited to connect each SPAD to its dedicated electronic, leading to a minimization of the overall number of interconnections crossing the integrated system, which is one of the main issues in high-density arrays.

Due to the high number of channels, the maximum achievable count rate is set by the external PC, indeed the affordable throughput is still the main limitation. Besides, in a TCSPC measurement not all the acquisition chains are simultaneously working due to the targeted low detection probability per excitation pulse (typically 1-10%), therefore resource sharing is intrinsically feasible. We set the affordable throughput to 10Gb/s, which is well beyond the state of the art, and tailored the number of acquisition chains starting from this limit, achieving in this way a more efficient resource utilization, without impairing on the count rate. A dynamic-routing logic connects the detector array to the lower number of acquisition chains. In order to sustain this throughput, the system features a USB 3.0 connection and a 10G Ethernet link through copper cable/fiber optics. The USB 3.0 connection has been chosen since it's a wide spread standard, whereas the 10G link is meant for very demanding applications.

Five fast Time-to-Amplitude Converters (TACs) have been designed in order to measure the arrival time of photons with tens-of-picoseconds precision. The main feature of these converters is the high counting efficiency achieved by means of an extremely low dead time (12.5 ns).

The preliminary results obtained with the first developed prototype are presented.

10229-11, Session 3

Photon counting detector package optimized for laser time transfer with sub??picosecond limiting precision and stability

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The laser time transfer ground to space is an attractive technique to compare the ultra-stable clocks on ground and in space. The photon counting approach enables to reduce significantly the systematic errors of the measurement chain. For the space mission nominated for the next decade the precision and long term detection delay stability requirements are on sub-picosecond level. We have developed a new SPAD detector package for laser time transfer ground to space with extremely high timing precision and stability. It is based on 100 µm or 200 µm diameter K14 series SPAD chip. The limiting precision of laser time transfer characterized by a time deviation TDEV is well below 100 fs for 100 s averaging time. The long term timing stability is better than 1 ps over days of operation. The detector package is constructed on a basis of electronics components for which the space qualified equivalents are available. The device construction, tests and results will be presented in detail.

10229-12, Session 3

Development of a high-performance multichannel system for time-correlated single photon counting

Pietro Peronio, Alessandro Cominelli, Giulia Acconcia, Ivan Rech, Massimo Ghioni, Politecnico di Milano (Italy)

Time-Correlated Single Photon Counting (TCSPC) is an effective technique for measuring fast and weak optical signals, thanks to the achievable high temporal resolution and single photon sensitivity. These features make it suitable for a huge variety of applications, especially those related to life science, where the maximum power of the laser has to be limited in order not to damage the sample. On the other hand, the main drawback of this technique is the intrinsic long acquisition time, which has constantly fostered the development of faster and faster TCSPC systems.

In recent years, the increase of the parallelism level has been the main trend followed by the development of TCSPC system, which feature higher and higher count rate capabilities, but with timing performance not even comparable with the best state-of-the-art single channel systems.

We present the design of a complete TCSPC system meant for overtaking the existing trade-off between parallelism level and performance. This system will deeply impact on many TCSPC applications (e.g. High Content Screening) which strongly demands for both high performance and short acquisition times, leading the way to performing analyses that have never been doable so far.

In order to overcome the existing trade-off, every part of the system has to be tailored and feature the best in-class performance: custom technologies have been employed for designing state-of-the-art single photon detectors, whereas CMOS technology has been preferred for the read-out electronics. The exploitation of different technologies has been made feasible by means of Through Silicon Vias (TSVs), which will connect the two different chips.

10229-13, Session 3

Development and characterization of an 8x8 SPAD-array module for gigacount per second applications

Francesco Ceccarelli, Angelo Gulinatti, Ivan Labanca, Ivan Rech, Massimo Ghioni, Politecnico di Milano (Italy)

In recent years the development of Single-Photon Avalanche Diodes (SPADs) had a big impact on single-photon counting applications that require high-performance detectors in terms of Dark Counting Rate (DCR), Photon Detection Efficiency (PDE), afterpulsing probability, etc. Among these, it is possible to find applications in single-molecule fluorescence spectroscopy that suffer from long-time measurements, due to the necessity of reaching proper statistical accuracy. In these applications SPAD arrays can be a solution in order to shorten the measurement time, thanks to the high grade of parallelism they can provide. Moreover applications in other fields (e.g. astronomy) demand for large-area single-photon detectors, able also to handle very high count rates, up to few Gcount/s.

For these reasons we developed a new single-photon detection module, featuring a 8x8 SPAD array. Thanks to a dedicated silicon technology, the performance of the detector have been finely optimized, reaching a 49% detection efficiency at 550 nm, as well as low dark counts (2 kcount/s maximum all over the array, at a working temperature of -15 °C), with an overvoltage of 6 V. This module can be used in two different modes: the first is a multi-spot configuration, where each pixel works as an independent detector, allowing the acquisition of 64 optical signals at the same time and considerably reducing the time needed for a measurement. The second operation mode instead exploits all the pixels in a combined mode, allowing the detection of a 64-times higher maximum photon rate (up to 2 Gcount/s), with only a small reduction of the detection efficiency when a suitable array of microlenses is used on the detector in order to avoid fill factor losses. In addition, this configuration provides also advantages in terms of dynamic range, that is not only moved toward higher count rates, but also extended by 10 dB with respect the multi-spot configuration. Finally, even if the system is used in the combined mode, it provides to the user an independent output for every SPAD, with electrical pulses synchronous with the photon arrival times. This last feature allows to attain photon number resolving capabilities, that allows us to propose this module also as a valid alternative to other photon counting solutions, such as the silicon photomultipliers (SiPM).

Since the module can operate in different conditions of overvoltage and temperature, a complete experimental characterization has been performed at different operating conditions: dark counts, detection efficiency, linearity, afterpulsing and crosstalk probability have been characterized.

10229-14, Session 4

High performance single photon detectors: where is the limit? *(Invited Paper)*

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Superconducting detectors based on nanowires enable light detection at the single photon level. While these devices are undergoing important improvements, operation combining near-unity detection efficiency with very high time resolution remains a challenge. We will report on our progress based on NbTIN nanowires that offer combining outstanding performances without any compromise: while the detection efficiency can now exceed 90%, the time resolution in the same device can be better than 15 ps. We will present recent results aiming at further improving detectors performances.

10229-15, Session 4

Superconducting nanowire single photon detector for coherent detection of weak signals *(Invited Paper)*

Gregory N. Goltsman, Mikhail Shcherbatenko, Yury V. Lobanov, Vadim V. Kovalyuk, Alexander A. Korneev, Moscow State Pedagogical Univ. (Russian Federation); Oliver Kahl, Karlsruher Institut für Technologie (Germany); Simone Ferrari, Wolfram H. P. Pernice, Karlsruher Institut für Technologie (Germany) and Fachhochschule Münster (Germany)

Traditionally, photon detectors operate in a direct detection mode counting incident photons with a known quantum efficiency. This procedure allows one to detect weak sources of radiation but all the information about its frequency is limited by the optical filtering / resonating structures used which are not as precise as would be required for some practical applications. In this work we propose heterodyne receiver based on a photon counting mixer which would combine excellent sensitivity of a photon counting detector and excellent spectral resolution given by the heterodyne technique.

At present, Superconducting-Nanowire-Single-Photon-Detectors (SNSPDs) [1] are widely used in a variety of applications providing the best possible combination of the sensitivity and speed. SNSPDs demonstrate lack of drawbacks like high dark count rate or autopulsing, which are common for traditional semiconductor-based photon detectors, such as avalanche photon diodes.

In our study we have investigated SNSPD operated as a photon counting mixer. To fully understand its behavior in such a regime, we have utilized experimental setup based on a couple of distributed feedback lasers irradiating at 1.5 micrometers, one of which is being the Local Oscillator (LO) and the other mimics the test signal [2]. The SNSPD was operated in the current mode and the bias current was slightly below of the critical current. Advantageously, we have found that LO power needed for an optimal mixing is of the order of hundreds of femtowatts to a few picowatts, which is promising for many practical applications, such as receiver matrices [3]. With use of the two lasers, one can observe the voltage pulses produced by the detected photons, and the time distribution of the pulses reproduces the frequency difference between the lasers, forming power response at the intermediate frequency which can be captured by either an oscilloscope (an analysis of the pulse statistics is needed) or by an RF spectrum analyzer. Photon-counting nature of the detector ensures quantum-limited sensitivity with respect to the optical coupling achieved.

In addition to the chip SNSPD with normal incidence coupling, we use the detectors with a travelling wave geometry design [4]. In this case, an NbN nanowire is placed on the top of a Si3N4 nanophotonic waveguide, thus increasing the efficient interaction length. For this reason it is possible to achieve almost complete absorption of photons and reduce the detector footprint. This reduces the noise temperature of the device together with the expansion of the bandwidth. Integrated device scheme allows us to measure the optical losses with high accuracy. Our approach is fully scalable and, along with a large number of devices integrated on a single chip can be adapted to the mid and far IR ranges where photon-counting measurement may be beneficial as well [5].

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10229-16, Session 4

Superconducting order parameter fluctuations in NbN/NiCu and NbTiN/NiCu bilayer nanostripes for photon detection

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A key performance figure of superconducting single-photon detectors is a low dark count rate, i.e., the spurious output signal without absorption of an optical photon. The functional principle of these detectors requires that they are operated very close to the critical current to allow for the formation of a resistive hotspot. In general, operation of a superconductor near the phase transition into the normal state is influenced by thermodynamic fluctuations of the superconducting order parameter. Strong fluctuations can locally suppress superconductivity and, thus, trigger unwanted output signals. We present results of our studies of superconducting order parameter fluctuations in NbN/NiCu and NbTiN/NiCu superconductor/ferromagnet (S/F) ultrathin bilayers and nanostripes. The NbN and NbTiN layers were grown using dc-magnetron sputtering on chemically cleaned sapphire single-crystal substrates. After rapid thermal annealing at high temperatures, the S films were coated with Ni0.5Cu0.5 overlayers with thicknesses of a few nm, using co-sputtering. Low-temperature tests confirmed that in all cases NiCu films were ferromagnetic with the Curie temperature of above 30 K. while both NbN and NbTiN nanostripes exhibited excellent superconducting properties with the critical current density at 4.2 K well exceeding 1 MA/cm2. The fluctuation-enhanced conductivity (paraconductivity) as well as magnetoconductivity of the NbN and NbTiN ultrathin S films were in excellent agreement with the parameter-free theory for order-parameter fluctuations in two-dimensional superconductors, confirming the validity of our approach. On the other hand, the presence of an F top layer changed the magnetotransport properties significantly. The temperature dependence of magnetoresistance demonstrated an unusual negative region in the S/F nanostructures that extended almost to room temperature and that was not present in the single S layer. Both paraconductivity and magnetoconductivity data fell below the

theoretical expectation, indicating a strong reduction of superconducting fluctuations. Such suppression of the fluctuation amplitude in S/F bilayers could be favorable to reduce dark counts in photon detectors and lead the way to enhance their performance.

10229-17, Session 4

Investigation of dark counts in innovative materials for superconducting nanowire single photon detector applications

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Superconducting nanowire single photon detectors (SNSPDs) have shown very good performance for the detection of single infrared photons by simultaneously combining high detection efficiency, good timing jitter with a very low intrinsic dark count rate. Recently special attention in the research community has been devoted to the physical origin of the observed dark counts and revealed the importance of various mechanisms involving the thermal activation of magnetic vortices in the superconductor. However, since SNSPDs so far have all been based on materials from the same family of superconductors, this insight does not enable a reduction in the dark counts. With this in mind we have investigated the phenomenon of dark counts in nanowires of two very different types of superconductors, namely superconductor/ferromagnet hybrids (using NbN/NiCu) and high temperature superconductors (using YBa2Cu3O7-x). For NbN/NiCu we find that in the temperature range from 4.2 K to 8 K the dark counts were reduced with respect to pure NbN nanowires and was probably dominated by single vortex entry from the edge of the nanowire. In the case of YBa2Cu3O7-x we find that also in this case the thermal activation of vortices generate the dark counts.

10229-18, Session 5

Satellite laser ranging in the near-infrared regime *(Invited Paper)*

Johann Eckl, Bundesamt für Kartographie und Geodäsie (Germany); K. Ulrich Schreiber, Technische Univ. München (Germany); Torben Schüler, Bundesamt für Kartographie und Geodäsie (Germany)

Exploiting the primary wavelength of the Nd:YAG pulse laser in Satellite Laser Ranging (SLR) has been hampered by the low quantum efficiency and high thermal noise of the solid state detectors in the past. However, recently suitable single photon sensitive receivers with promising operational parameters have become available. With the advent of InGaAs/InP compound - Single Photon Avalanche Diodes the situation has changed. Their quantum efficiency has reached 70% and the compound material of this diode is also well suitable for photon counting applications, when implemented in our recently published electrical circuit. It can be expected that these detectors will also be operable in the eyesafe regime around 1.55 μm, enabling eyesafe operation of SLR.

We have implemented and investigated the properties of this diode for its suitability for SLR at the Nd:YAG fundamental wavelength with respect to efficiency and its timing properties at the Geodetic Observatory Wettzell. The results are presented in this paper. In addition, we will compare these new detectors to the conventional receivers in laboratory tests as well as satellite ranging measurements. Finally, we will give an estimate of the photoelectron statistics in satellite laser ranging for different operational parameters of the Wettzell Laser Ranging System.

10229-19, Session 5

Satellite and Lunar laser ranging in infrared

Clement Courde, Jean-Marie Torre, Observatoire de la Côte d'Azur (France)

During this presentation we will report on the implementation of an InGaAs single photon avalanche photodiode at the Grasse LLR station. We will describe how infrared telemetry improves satellite and Lunar laser ranging. Our first results show that infrared detection permits to improve the link budget and allows measurements during the new and the full Moon periods, two very noisy periods.

10229-20, Session 5

Evaluation of performance of silicon photomultipliers in lidar applications

Sergey L. Vinogradov, PN Lebedev Physical Institute (Russian Federation)

Silicon Photomultipliers (SiPMs) are a well-recognized new generation of photon number resolving avalanche photodetectors. A number of SiPM advantages – a high gain with an ultra-low excess noise of multiplication, multi-pixel architecture, relatively low operating voltage – makes them very competitive in a growing number of applications. Challenging demands for a LIDAR receiver in high sensitivity starting from single photons, superior time-of-flight resolution, robustness including surviving at bright light flashes and others are expected to be feasible for the SiPMs. Despite some known drawbacks, namely crosstalk, afterpulsing, dark noise, limited dynamic range, SiPMs are already considered as promising substitutes for conventional APDs and PMTs in LIDAR applications. However, these initial considerations are based on a rather simplified representation of the SiPM as a generic LIDAR receiver described by generic expressions (e.g. signal-to-noise ratio with respect to signal, background, and noise power disregard light pulse timing).

This study is focused on a comprehensive evaluation of SiPM taking into account all essential features of SiPM, which could affect applicability and performance of these photodetectors for LIDARs. Namely, a nonlinearity of an output SiPM response due to a limited number of pixels, a dependence of pixel recovery dynamics on incident light intensity, an excess noise due to correlated processes of crosstalk and afterpulsing, are analyzed utilizing the well-established framework of analytical probabilistic modeling of SiPM photon number and time resolution. Evaluation results provide the comparison of competitive SiPM samples and anticipate the development of a next SiPM generation with the higher density of pixels, faster pixel recovery, and shorter single electron response.

10229-21, Session 5

Quantum state characterization by photon-number-resolving detectors

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Measuring quantum states of light is at the basis of both the investigations of fundamental Quantum Optics and of the applications to Quantum Information. Several different detection strategies can be exploited to measure the different aspects of light. For instance, optical homodyne detection addresses the wave-like properties of optical states while direct detection explores the particle-like features. Moreover, new

hybrid schemes addressing both wave-like and particle-like aspects of light have recently been introduced.

As to direct detection, different intensity regimes can be investigated by either single-photon detectors, photon-number resolving (PNR) detectors or macroscopic detectors. In particular, PNR detectors can give access to the number of photons in pulsed states, thus allowing the reconstruction of the photon-number statistics, of auto- and cross-correlation functions that are necessary for a thorough characterization of optical states.

Among the many kinds of PNR detectors available nowadays (also including fiber-loop detectors, visible-light photon counters, transition-edge sensors and superconductive nanowires), we used hybrid photodetectors (HPDs) and Si-photomultipliers (SiPM) that have the advantage of a rather easy operation at room temperature. Of course such detectors are also affected by imperfections, such as a limited dynamic range and rather low repetition rate (HPDs) or dark count and cross talk (SiPM). Moreover, both classes of detectors have rather low quantum efficiencies (about 50%).

To extract information from the outputs of PNR detectors, it is necessary to develop a suitable description of the operation of the detectors and of the detection chain. To this aim we elaborated a self-consistent calibration strategy for the detectors to be applied to the very light under investigation and yielding the values of the parameters characterizing the detectors (gain, dark-count rate, cross talk...). The obtained calibration values are then used to evaluate shot-by-shot detected-photon numbers and the values of the parameters are used to interpret the results in order to take into account all the imperfections of the detectors.

By applying such data analysis to HPDs and SiPMs, we demonstrated the reconstruction of photon-number statistics of classical and nonclassical states, also endowed with nontrivialm statistics. We also measured photon-number correlations at different orders with the aim of better characterizing the nature of the states. In spite of the rather low values of quantum efficiency and of the imperfections of the detectors, we could also demonstrate the nonclassical nature of the states by verifying the violation of some inequalities involving correlations at different orders. Finally, by exploiting the existence of nonclassical correlations in bipartite states, we generated non-Gaussian and sub-Poissonian conditional states.

10229-22, Session 5

Ultrahigh optical responsivity of semiconducting asymmetric nanochannel diodes for photon detection

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The asymmetric nano-channel diode (ANCD), also called the self-switching diode, is fundamentally a new type of 2-dimensional electron gas (2DEG) semiconductor nanodevice that, unlike a conventional diode, relies on the device nanostructure and field-controlled transport in a ballistic nanometer-width channel instead of barriers to develop its diode-like current-voltage (I-V) characteristics. In this presentation, we focus on optical properties of ANCDs, and demonstrate that they can act as very sensitive, single-photon-level, visible-light photodetectors. Our actual test devices exhibited 1-μm-long and ~100-nm-wide channels and were fabricated on an InGaAs/InAlAs heterostructure with a 2DEG layer, using electron-beam lithography, followed by reactive ion etching. The ANCD I-V curves were collected by measuring the transport current for the voltage-source biasing condition, both in the dark and under light illumination. The experiments were conducted inside a light-insulated cryostat, in the temperature range from 300 K to 78 K. As an optical excitation, we used 800-nm-wavelength, either continues-wave or 100-fs-pulsed light, generated by a commercial Ti:Sapphire laser. The impact of the light illumination was very clear, and at low temperatures we observed a significant (up to 1 ?A for 78 K) photocurrent for the incident optical power as low as 1 nW, with a limited dark-current background. Most interestingly the magnitude of the device optical responsivity increased linearly over many orders of magnitude with the decrease of the optical power, reaching the value of ~800 A/W at the 1-nW excitation. We expect from this linearly increasing responsivity trend that we should be able to reach the responsivity around 25000 A/W, needed for single photon level light detection. The physics of the photoresponse gain mechanism in ANCD arises from a vast disparity between the picosecond transit time of electrons travelling in the 2DEG nanochannel and the up to microsecond lifetime of holes pushed towards the device substrate.

10229-23, Session PS

Authentication performance of the double-random-phase-encoding method with photon counting technique

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In this paper, we try to evaluate the authentication performance of the double-random-phase-encoding (DRPE) method with photon counting (PC) technique and compare the results with the case there is no PC method. Firstly, several gray-scale images are encoded by DRPE and then PC is applied on the amplitude part of the DRPE images. Decrypted DRPE-PC images are not visually recognizable but still can be verified with different image comparison metrics. Experiments are conducted for the different photon numbers and the results are compared. Several image comparison metrics are evaluated and the results for DRPE-PC and DRPE are compared.

10229-24, Session PS

An ultrafast thermoelectric sensor for single-photon detection in a wide range of the electromagnetic spectrum

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Single-photon detectors, capable to determine the photon energy and to provide high count rates, are demanded in quantum electronics, astrophysics, high energy physics, quantum informatics, telecommunication systems, quantum metrology, measuring systems for applications in medicine, homeland security and other fields. Among the developments of the last 17 years, superconducting nanowire single-photon detectors are considered as the most promising [1]. The thermoelectric single-photon detector possesses similar characteristics [2, 3]. In [4, 5] is shown that by decreasing the thickness of thermoelectric layers of multilayer sensor of thermoelectric detector is possible to obtain transducers for registration of photons with count rates higher than tens gigahertz. However, the thinner is the thermoelectric layer, the lower is it's electrical resistance, that may be an obstacle for the registration of the voltage on the sensor. The latter barrier can be overcome if the resistance of the measuring circuit is lower than the resistance of the thermoelectric layer. The problem can be solved by using a superconducting material. We propose a new type of a thermoelectric detector with a sensor consisting of two superconducting layers and a thermoelectric layer between them [6]. In the present work is performed computer simulation of heat propagation processes taking place after absorption of single photons of 1 eV-1 keV energy in the three-layer sensor of the thermoelectric detector. The calculations were based on the heat conduction equation and were carried out by the matrix method for differential equations.

We considered different geometries of the sensor in which are used (La,Ce)B6 hexaboride as a thermoelectric layer, superconducting absorber and heat sink layers of Nb, Pb and YBCO. It is shown, that by changing materials and sizes of the sensor's layers is possible to obtain transducers for registration of photons within the given spectral range with the required energy resolution and count rate. It is demonstrated that such a sensor has a number of advantages, as well as improved characteristics which give ground to consider the thermoelectric detector as a real alternative to superconducting nanowire single-photon detectors.

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10229-25, Session PS

Tracks detection from high-orbit space objects

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Previously developed high-orbit cosmic objects (CO) detection algorithms are based on a signal registration in the frame with a significant storage time and registration of a sufficiently large number of point objects and their analysis.

A complex algorithm of each frame registration for significantly less time in a limited series of weak tracks frames from high-orbit cosmic objects is proposed. Including tracks from a discrete structure. That is, tracks with some number of pixels with unregistered signal.

During accomplishing such detection tasks preprocessing is performed, considering catalogued objects. After that weak track to a point detected object frame conversion is carried out. Linear filtering by synthesized masks performs this transition. This filtering further smooths the Gaussian noise.

Next frame package is formed with a shift in the intended direction of ?O movement. Median filtering frames package is carried out. This operation is performed for such areas of each frame, that are projected onto all other frames of the package. Then, a search for the maximum signal value after median filtering and its comparison with a detection threshold are carried out. The detection threshold is determined based on an analysis of the resultant frame block noise and the number of frames in the package.

In the case of wide-angle optical electronic systems usage in order to minimize the processing, it is possible to emphasize areas in each frame, where with a high a priori probability CO is located.

To test the effectiveness of the proposed algorithm CO weak tracks are modelled based the real night sky shots. Frame package processing was carried out considering read noise. Limit specs are listed, that are based on the photoelectron detection statistics for specific optoelectronic systems.

The effectiveness of the proposed algorithm is shown, which increases the penetrating ability of optoelectronic systems, nearly two magnitudes.

10229-26, Session PS

Short-range energy budget simulator of single photon lidar demonstrator

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The compact single photon lidar demonstrator dedicated for asteroid rendezvous missions has been designed and realized in our laboratory two years ago. The instrument provides crucial data on altitude and terrain profile for altitudes exceeding 5 km with a precision of less than 10 cm fulfilling the Rayleigh criterion. One of the calibration procedure of demonstrator is the positioning of receiver and transmitter optics related to detector and laser and the aligning of transmitter and receiver optical common paths. To improve this particular indoor calibration procedure the new simulator of single photon energy budget during short range operation has been created. The comparison of simulated and experimental data will be presented and discussed.

10229-27, Session PS

Time transfer capability of standard small form factor pluggable laser modules based on photon counting approach

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We are reporting on timing parameters of commonly used standard Small Form Factor Pluggable (SFP) laser modules using single photon counting method. Photon counting is a promising approach for laser time transfer via optical fiber communication hardware. The sub-picosecond precision and stability may be achieved. We have performed several experiments with the aim to measure main parameters of the modules, such as time delay precision, time stability and temperature stability, all being critical for optical time transfer applications. Two standard 16 Gbit and 10 Gbit 850 nm SFP modules were examined. The ultimate precision of possible time transfer of 800 fs for averaging times of hours was achieved. The modules together with their driving circuits exhibited very good temperature stability. The temperature drift as low as 300 ± 200 fs/K was measured. The achieved timing parameters will enable to use the standard SFP modules for a new method of two way time transfer where the time differences between two distant time scales are measured in parallel to data transfer on existing optical data links without any communication interference.

10230-1, Session 1

Recent experimental progress towards global quantum communication *(Invited Paper)*

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Quantum communication can provide information theoretical security communication based on the basic principle of quantum mechanics. Here, I would like to present the recent experimental progress in our group towards global quantum communication, including measurement device independent QKD over in the lab and metropolitan network, quantum teleprotation and entanglement swapping over metropolitan network, trust node based quantum main trunk line and free space quantum communication.

10230-2, Session 1

Quantum relays using semiconductor entangled light sources *(Invited Paper)*

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Quantum relays [1] are a key technology to extend the range of present quantum key distribution (QKD) systems and future optical quantum networks. The underlying physical principle is to perform teleportation of photonic input quantum bits, which can effectively reduce noise in long-distance photon-transmission scenarios. Most interesting for QKD is that the security of the quantum channel is unconditionally guaranteed, even if the entanglement resource or the relay itself are located at untrusted nodes of the network.

Photon sources based on non-linear processes have a long history in photonic teleportation experiments, enabling pioneering experimental work. However, the number statistics of these sources follow a Poissonian distribution, typically increasing error rates and requiring operation at low intensities and implementation of sophisticated security protocols. Semiconductor quantum dots (QD) have proven to be a promising alternative entanglement source, with true single-photon emission enabling intrinsic security for applications.

In the past, we have shown that operation of a QD-driven quantum relay is possible at short wavelength, with experimental error rates suitable for the implementation of secure communication protocols [2]. In more recent experiments, we demonstrate a system with a QD photon source that is exclusively operating at telecom wavelength [3], enabling for the first time a quantum relay with sub-Poissonian photon statistics and full compatibility with existing telecom-fiber infrastructure. Detailed characterization reveals high fidelity operation and teleportation of arbitrary input qubits. The results prove that quantum-dot entangled photon sources are a promising platform for the development of practical and network-compatible quantum-relay technology.

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10230-3, Session 1

Spectroscopy of non-interfering photons through nonlinear integrated optics Mach-Zehnder interferometer

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Since the last decades, quantum optics has become a key field of research, allowing fundamental investigations of quantum physics principles and leading to a complex variety of novel quantum technologies. In this framework, integrated optics (IO) technologies allow implementing complex quantum circuits that can offer significant outcomes in this research areas, otherwise difficult to reach using more traditional bulk approaches.

Exploiting the multi-year expertise in Micro Electro Optical Systems (MEOS) technologies, developed at our laboratory particularly concerning the Lithium Niobate (LiNbO3, LN) technological platform, it was decided to implement a series of experimental experiences highlighting the quantum nature of light, in order to investigate quantum phenomena and put in evidence the advantages offered by integrated optical circuits when active and non-linear integrated components are applied.

In this view it was implemented a non-linear Mach-Zehnder Interferometer (MZI), fully composed by integrated optical elements. The main interferometric geometry was obtained by using two off-the-shelf 50:50 directional single mode fiber couplers, whereas the MZI arms were equipped one with a single mode Er:LiNbO3 optical waveguide and the other one with an undoped LiNbO3 single mode optical waveguide, both obtained by Ion Implantation. The first one acts as a non-linear component whereas at the second one an electric field is applied to obtain an optical phase shift.

The injection in the integrated optical circuit of a 980nm wavelength laser radiation - interacting with the Er doped waveguide placed only on one arm of the MZI and producing both up and down converted photons, following Er energy terms in LN matrix - allowed to record complex structured interferogrammes.

The obtained interferogrammes could be ascribed exclusively to the pump photons, as all frequency conversion events are localized in one arm of the Interferometer, therefore without possibility to generate direct interference.

By applying a conventional Fourier Transform elaboration to the obtained interferogrammes, it is possible to obtain multiple peak spectra that tightly match the typical transition spectrograms of Er:LiNbO3 when excited by 980nm radiation. Similar results were obtained even in presence of a narrow pass band filter (980nm ± 25nm) at the MZI output, preventing the detection of all converted photons, thus confirming the solely contribution of pump photons to the generation of the interferometric records.

In other words, it is possible to perform a spectrometry of the non-interfering photons generated in the non-linear arm through the interaction of this element with the source photons, by analyzing the modulated signal produced at the detector exclusively by the pump photons.

Conversely, when a 1310nm laser source (not absorbed by Er3+) was applied, the complexity of the recorded interferogrammes disappeared, with the corresponding Fourier Transforms giving rise to a single fundamental peak.

In this work the experimental apparatus, fully realized by integrated

optical components, is described together with the most interesting results obtained in different experimental conditions.

Finally, a possible interpretation of the observed phenomena is proposed and preliminarily discussed.

10230-4, Session 1

Reducing detection noise of a photon pair in a dispersive medium by controlling its spectral entanglement

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Single-photon sources are crucial components for the implementation of quantum communication protocols. However, photons emitted by some of the most popular types of realistic sources are spectrally broadband. Due to this drawback, the signal emitted from such sources is typically affected by the effect of temporal broadening during its propagation through telecommunication fibers which exhibit chromatic dispersion. Such problem can be observed e.g. when using sources based on the process of spontaneous parametric down-conversion (SPDC). In the case of long-distance quantum communication temporal broadening can significantly limit the efficiency of temporal filtering. It is a popular method, which relies on the reduction of the duration time of the detection window, used for decreasing the number of registered errors.

In this work we analyzed the impact of the type of spectral correlation within a pair of photons produced by the SPDC source on the temporal width of those photons during their propagation in dispersive media. We found out that in some situations this width can be decreased by changing the typical negative spectral correlation into positive one or by reducing its strength. This idea can be used to increase the efficiency of the temporal filtering method. Therefore, it can be applied in various implementations of quantum communication protocols.

As an example of the application we subsequently analyzed the security of a quantum key distribution (QKD) scheme based on single photons. The investigation was performed for the configuration with the source of photons located in the middle between the legitimate participants of a QKD protocol (called typically Alice and Bob). We demonstrated that when the information about the emission time of the photons produced by the SPDC source is not distributed to Alice and Bob, the maximal security distance can be considerably extended by using positively correlated photons, while in the opposite case strongly (no matter positively or negatively) correlated photons are optimal. We also found out that the results of our calculation may be very sensitive to the spectral widths of the photons produced by the SPDC source. In addition, we concluded that in realistic situation Alice and Bob would have to optimize their source over both the spectral widths of the generated photons and the type of spectral correlation in order to maximally extend the security distance.

The results of our work are, in particular, important for the QKD systems utilizing commercial telecom fibers populated by strong classical signals. In those systems temporal filtering method can be used to reduce not only the dark counts registered by the detection system, but also the channel noise originating from the process of Raman scattering, which is the main factor limiting their performance.

10230-5, Session 2

Quantum digital signatures in optical fiber networks *(Invited Paper)*

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To date, the field of quantum communications has mainly focused on quantum key distribution (QKD) – to the point where commercial systems are now available. By employing either single photons or weak coherent states as the information carriers, QKD allows the pairwise generation of secure keys for use in point-to-point encryption. Quantum digital signatures (QDS) offer complementary functionality to that of QKD to create secure digital signatures which provide information-theoretically secure guarantees of the authentication, non-repudiation and transferability of signed messages.

Early experimental demonstrations of QDS operated with highly specialized custom hardware in a laboratory environment and transmitted over short lengths of optical fiber in controlled conditions. The first experimental demonstration of QDS required quantum memory, operated over 5 meters of specialized optical fiber and required complex active feedback control systems and thermal isolation. Ongoing developments of the underlying theoretical protocols lead to many of these restrictive requirements being removed with each subsequent iteration of the experimental demonstrations. However, the previous demonstrations remained laboratory-based with specific optical configurations that offered limited compatibility with the global telecommunications optical fiber infrastructure.

More recently we have reported a QDS system operating over several tens of kilometers of dark installed standard telecommunications optical fiber. The QDS system employed a QKD system operating at a wavelength of 1550 nm and only modified the classical post-processing of the data, leaving the optical systems unchanged. Therefore, this experiment demonstrates the potential that commercially available QKD systems can be adapted for use with QDS with minimal changes – dramatically extending the practicality of this application of quantum communications.

10230-6, Session 2

Device-independent quantum key distribution with single-photon sources *(Invited Paper)*

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The concept of the Device-Independent Quantum Key Distribution (DI-QKD) constitutes the minimalist paradigm for quantum cryptography, in which the security of the distributed secret key is fully assured by the statistical properties of the data being shared between the parties that perform a quantum-based protocol. In particular, the secrecy of the distributed key is ultimately guaranteed not only thanks to the quantum nature of the underlying scheme, but also without making any assumptions about the operation of the devices being employed.

Such a conservative approach is possible thanks to the non-local correlations exhibited within the shared data, i.e., the correlations of genuine quantum origin that, due to violation of a particular Bell inequality, cannot be explained by any form of common randomness pre-available to the parties. Such violation, however, must be revealed without performing any post-selection on the data, what would then open the so-called detection loophole and jeopardize the security of the protocol.

In spite of the tremendous advances recently made to achieve higher detection efficiencies in Bell-violation experiments, DI-QKD remains a very experimentally difficult task due to the exponential increase of loss in the channel, e.g., implemented with optical fibres, with the distance separating the parties involved. Here, we describe a new and plausible solution to overcome the crucial problem of channel loss in the frame of DI-QKD optical implementations.

In particular, we propose a novel protocol inspired by the entanglement swapping schemes, which by the usage of the state-of-the-art (e.g., quantum-dot-based or heralded) single-photon sources has potential, for the first time, to be implementable with current photonic and linear optics technologies. While allowing for any transmission losses that only decrease the rate of the key distribution without creating vulnerability, it tolerates overall detection efficiency at the 90% level even when requiring strict device-independence.

We compare our scheme against protocols that involve sources based on spontaneous parametric down-conversion (SPDC), in order to explicitly

show and explain why such SPDC-based proposals—even when enhanced by the entanglement swapping or qubit amplification techniques—are then largely outperformed when physical imperfections are rigorously taken into account.

10230-7, Session 2

High fidelity spin-orbit transduction of an entangled photonic qubit in vortex fibers

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Quantum networks are believed to enable applications beyond the reach of their classical counterparts. These networks exploit the non-classical correlations between entangled particles and rely on the ability of their nodes to create, distribute, and manipulate complex entangled states. Recent years have brought interest to multi-dimensional and hyper-entangled states, fueled in part by their potential to increase capacity and combat losses intrinsic to long-distance transmission in optical fibers. Vortex states that carry orbital angular momentum (OAM) form an infinite family of mutually orthogonal states and hence look particularly attractive for this purpose.

In this talk we will discuss the successful and reversible conversion of a photonic degree of freedom entangled with that of another photon while both photons are travelling in optical fibers. By utilizing a conventional nonlinear scheme we create a polarization entangled pair at the telecom band, use photon frequency dimensions to separate the two photons, and route each in a different fiber. One fiber is a regular single mode fiber that guides the first photon to its detector station. The second photon travels towards the second detector station via a special vortex fiber, which has a specially designed mode structure allowing for the existence of OAM modes. Long-period gratings at the end of the fiber facilitate mode conversion from polarization to OAM states and back. The received quantum states are fully characterized. Tomography reveals final states whose fidelity to the initial state could be as high as 0.95.

The limiting factors to the conversion to and propagation of OAM states in special fiber are a small amount of lumped modal loss, its variable misalignment due to environmentally induced fiber birefringence, as well as temporal drifts during the measurements. We devise a method to characterize two apparent loss elements. Using the numbers extracted from the data and additionally modelling the drift in the depolarizing quantum channel with Kraus operators we are able to fit the experimental data with 0.94-0.96 fidelity.

10230-9, Session 2

Quantum fingerprinting without a shared phase reference

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We present a quantum fingerprinting scheme based on two-photon interference which does not require a fixed phase reference between parties preparing data strings to be compared. Effects of photon statistics and detector imperfections are analyzed in the limit of high channel loss.

10230-10, Session 3

Highly-stable optical frequency generation based on laser cooled and trapped ions *(Invited Paper)*

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The traditional optical frequency standards use ultra-pure molecular gases as the spectroscopic references for the locking of the generated optical frequency of narrow-linewidth highly-coherent lasers. But the novel frequency standards are based on quantum effects with a single atom or ion in the ground motional state that can works as a quantum atomic absorber. Excitation of the single ion into a forbidden transition gives an opportunity to stabilize a highly coherent laser at the optical frequency of order hundreds of THz with the sub-Hz level uncertainty. This unprecedented relative stability of a highly-coherent laser crossing the level 10-16 and beyond is a promising way to define the "optical atomic clocks" as an ultimate time and frequency standard followed by the redefinition of SI units second and meter. New trends in these ultimate optical frequency standards initiated an effort to establishing a joined laboratory in the Czech Republic where a research of quantum mechanical interactions of trapped ions with highly-coherent laser lights would be realized. The Institute of Scientific Instruments Brno and Palacky University Olomouc have put together an experimental research infrastructure for 40Ca+ ion trapping, cooling, experiments of quantum mechanics and spectroscopy in joined laboratory in Brno. We report on the first set of results including ions generation, trapping into Paul trap, laser cooling and spectroscopic measurements of multi-level electronic structure of the ion and the occurrence of dark resonances in the fluorescence signal. The work includes a scheme of the experimental infrastructure for 40Ca+ ion trapping and cooling, vacuum chamber, Paul trap, trap radiofrequency control and excitation lasers control and their referencing to an optical frequency comb disciplined by an active H-maser. The state-of-the-art of the optical frequency transfer over long-haul communication fibers is the next topic of the work. Except the optical atomic clocks experiments, the utilization of this novel setup is in studies of an unsolved quantum behaviour of ions in strong nonlinear potential, mutual ions' interaction including interaction with inner ions' levels addressed optically.

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10230-11, Session 3

Dynamics of entanglement near periodic plasmonic nanostructures

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In the field of quantum information and quantum computing, entanglement plays an essential role. Entanglement preservation is an important issue as realistic quantum systems are affected by decoherence and entanglement losses due to the interaction with their environment. For example, in spite of an exponential decay of a single qubit, the entanglement between two qubits may completely disappear at a finite time; a phenomenon known as "entanglement sudden death" [1]. Recently, interest has been given in cases that qubits can be strongly coupled to plasmonic nanostructures, like, for example, an one-dimensional plasmonic waveguide [2] or a two-dimensional lattice of metal-coated dielectric nanoparticles [3]. In such systems the strong interaction with the surface plasmons leads to significant entanglement between the two qubits. Here, we consider the interaction of two initially entangled qubits interacting individually with a two-dimensional lattice of metal-coated dielectric nanoparticles. We consider two cases for the qubits, a pair of regular two-level systems and a pair of V-type systems where one transition is the qubit and the other level acts as an umbrella level [4]. We consider the entanglement dynamics for different initial conditions of the qubits. The specific plasmonic nanostructure leads to strongly modified spontaneous emission rates of individual quantum

systems (strong suppression in certain cases) and, in addition, to strongly anisotropic Purcell effect for orthogonal dipoles, that in turn can be used for simulating quantum interference in spontaneous emission [5]. We use these effects for significantly prolonging entanglement dynamics near the plasmonic nanostructure in both cases, in comparison to the cases that the qubits are in free space.

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10230-12, Session 3

852nm triggered single-photon source based on single cesium atoms trapped in a microscopic optical tweezer

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Single-photon source is one kind of important quantum resources for fundamental research in quantum optics, quantum communications, and the Bose sampling quantum computation. Based on periodical excitation of single cesium atoms trapped in a microscopic optical tweezer, formed by a strongly-focused 1064nm fundamental-mode cw laser beam, 852nm triggered single photons have been demonstrated and characterized. The 852nm nanosecond excitation laser pulses with a high ON/OFF ratio and a repetition rate of 10MHz are achieved by chopping a cw single-frequency 852nm laser beam by using of a temperature-stabilized waveguide-type intensity electro-optical modulator (EOM). The spontaneous emission heating of trapped single atoms arising from periodical resonant excitation limits the trapping lifetime, and this seriously affects the single-photon source. To extend the trapping lifetime, a proper laser cooling phase is employed after each group of periodical excitation. With optimized experimental time sequence, the Rabi oscillation of single atoms between the ground state (6S_1/2 (Fg=4)) and the excited state (6P_3/2 (Fe=5)) is clearly observed. The triggered 852nm single photons have been characterized by using of Hambury Brown - Twiss (HBT) measurement, and a strong photon anti-bunching is realized. The single photon purity of our single-photon source is ~ 91%, and the single photon extraction efficiency is ~ 2.1%. References: [1] Phys. Rev. A, Vol.94 (2016) 013409; [2] Appl. Phys. Express, Vol. 9 (2016) 072702; [3] Physica Scripta, Vol. 84 (2011) 025302

10231-1, Session 1

Tip-enhanced Raman spectroscopy for nanoscale chemical analysis and imaging *(Invited Paper)*

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Tip-enhanced Raman Spectroscopy (TERS) is a nanoscale chemical analysis and imaging method with a spatial resolution on the order of 10 nm. TERS is similar to SERS, and relies on enhancement of the local electromagnetic field in the vicinity of a plasmonic nanostructure that is scanned over a sample by means of a scanning probe microscope, using either AFM or STM feedback. The local enhancement of Raman scattered light is many orders of magnitude, large enough to render monomolecular films spectroscopically visible that would otherwise be optically too thin to be analyzed with conventional vibrational spectroscopy.

The working principle and experimental realization of TERS will first be presented [1]. An important advance concerns the production long-lived silver TERS tips that, thanks to the presence of a chemical protection layer, live for many weeks as opposed to the typical lifetime of ≈1 day for bare Ag tips [2]. The focus of this presentation will be on applications of TERS to the spatially resolved chemical analysis of molecular nanomaterials, including graphene, self-assembled monolayers [3], and a novel class of materials, 2D polymers [4].

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10231-2, Session 1

SERS substrates for in-situ biosensing

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Recent years have seen a rapid progress in the field of surface-enhanced Raman spectroscopy (SERS) which is attributed to the thriving field of plasmonics [1]. SERS is a susceptible technique that can address basic scientific questions and technological problems. In both cases, it is highly dependent upon the plasmonic substrate, where excitation of the localized surface plasmon resonance enhances the vibrational scattering signal of the analyte molecules adsorbed on to the surface [2]. In this work, using finite difference time domain (FDTD) method we investigate the optical properties of plasmonic nanostructures with tuned plasmonic resonances as a function of dielectric environment and geometric parameters. An optimized geometry will be discussed based on the plasmonic resonant position and the SERS intensity. These SERS substrates will be employed for the detection of changes in conformation caused by interactions between an aptamer and analyte molecules. This will be done by using a microfluidic channel designed within the configuration of the lab-on-a-chip concept based on the intensity changes of the SERS signal. More efficient and reproducible results are obtained for such a quantitative measurement of analytes at low concentration levels. We will also demonstrate that the plasmonic substrates fabricated by top down approach such as e-beam lithography (EBL) and laser interference lithography (LIL) are highly reproducible, robust and can result in high electric field enhancement. Our results demonstrate the potential to use SERS substrates for highly sensitive detection schemes opening up the window for a wide range of applications including biomedical diagnostics, forensic investigation etc.

Acknowledgement:

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10231-3, Session 1

SERS investigations and electrical recording of neuronal networks with three-dimensional plasmonic nanoantennas

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Biological systems are analysed mainly by optical, chemical or electrical methods. Normally each of these techniques provides only partial information about the environment, while combined investigations could reveal new phenomena occurring in complex systems such as in-vitro neuronal networks. Aiming at the merging of optical and electrical investigations of biological samples, we introduced three-dimensional plasmonic nanoantennas on CMOS-based electrical sensors [1]. The overall device is then capable of enhanced Raman Analysis of cultured cells combined with electrical recording of neuronal activity. The Raman measurements show a much higher sensitivity when performed on the tip of the nanoantenna in respect to the flat substrate [2]; this effect is a combination of the high plasmonic field enhancement and of the tight adhesion of cells on the nanoantenna tip. Furthermore, when plasmonic opto-poration is exploited [3] the 3D nanoelectrodes are able to penetrate through the cell membrane thus accessing the intracellular environment.

Our latest results (unpublished) show that the technique is completely non-invasive and solves many problems related to state-of-the-art intracellular recording approaches on large neuronal networks.

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10231-4, Session 2

Parallelization of single nanoparticle biosensors *(Invited Paper)*

Wolfgang Fritzsche, David Zopf, Jacqueline Jatschka, André Dathe, Andrea Csaki, Matthias Thiele, Gabriele Schmidl, Guangrui Li, Ondrej Stranik, Sophie Thamm, Leibniz-Institut für Photonische Technologien e.V. (Germany)

There is steady increasing demand for a reliable and sensitive detection of a broad range of biomolecules. Among various different approaches for detection, our group is interested in the use of localised surface plasmon resonances (LSPR) as a transducer for the biomolecular binding. The LSPR occurs in metallic nanostructures, where the spectral position and shape of the resonance can be engineered by the shape of the structure. We have used several approaches with a different degree of complexity for the formation of the nanostructures such as microfluidic synthesis of anisotropic particles [1], double concentric structures by colloidal lithography [2], pyramidal structures by template stripping and colloidal lithography [3] or by thermal annealing of thin continuous metal layers [4]. The reliable readout of the spectral position of the LSPR with very low noise is one of the key challenges in the biosensing process. The relatively simple detection can be realized on nanoparticles ensembles, but the step to the spectroscopy of a single particle is challenging [5]. Often only single or a small number of nanostructures can be measured at once and therefore a parallelization of these measurements is very time consuming. In our approach we have establshed hyper-spectral imaging combined with microscopy imaging system, which allows to record spectral properties of many particles simultaneously [6]. We were able to map spatial variation of the protein adsorption and to demonstrate the limitation of the ensemble LSPR measurement caused by the shape variation of the metallic nanostructures.

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10231-5, Session 2

Silicon-based high-index contrast sensing surface

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A Bloch Surface Wave (BSW) based sensor uses a multilayer Bragg reflector as a structure for the excitation of a surface wave within the band-gap of the reflector. The wavelength of the surface wave can be tuned inside the band-gap by adjusting the surface layer thickness. The BSW provides greater freedom in the operating wavelengths than Surface Plasmon Resonance (SPR), which is limited to a narrow range of metal dependent wavelengths. The BSW have longer propagation distances than the SPR waves due to smaller losses associated with dielectric materials and can be designed for both TE and TM polarisations in contrast to SPR which are only TM polarised. In this paper, an optical platform sensitive to changes in surface refractive index based on a thin silicon layer deposited on silicon dioxide on sapphire is experimentally demonstrated. The resonance is due to the layered structure and does not rely on additional processing. The excited TM polarised mode is compared to the multilayer BSW, SPR and the silicon-on-insulator (SOI) waveguide modes to show that the excited mode is not a high index guided mode but a BSW-like mode. Penetration depth of the excited mode at 1/e of the electric field is 150 nm into the water above the surface making it suitable for sensing thin analytes. The sensor is designed to operate around 820 nm wavelengths in the prism based Kretschmann-Raether configuration. A bulk sensitivity of 900 nm per refractive index unit (RIU) is experimentally demonstrated using water (n=1.33) and isopropyl alcohol (IPA, n=1.37) above the surface of the sensor. The demonstrated sensitivity is comparable to SPR based sensors but without the restriction in operating wavelength. The sensor is relatively insensitive to fabrication tolerances and can be designed to achieve a sensitivity of 1950 nm/RIU for operation at wavelengths of 1550 nm where the silicon-on-insulator (SOI) platform is now being widely used for photonic integration.

10231-6, Session 2

Plasmonically enhanced fluorescence biosensor with aptamer ligand

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The coupling of light to surface plasmons allows to strongly confine its electromagnetic field and enhance its intensity. These features are attracting for improving performance characteristics of various fluorescence–based analytical technologies. The near-field coupling of fluorophores that are used as labels with surface plasmons offers means to manipulate with emitted fluorescence light by the combination of enhanced excitation rate, distance depending quenching, and directional fluorescence emission. In affinity fluorescence biosensors, the surface of metallic nanostructures with tailored plasmonic characteristics is modified with ligands for specific capture of target analyte molecules. The probing of captured molecules with surface plasmons amplifies detected fluorescence signal which translates to the ability of detecting of lower amounts of specifically captured analyte from investigated samples and improved limit of detection. The paper will discuss the implementation aptamer-based surface plasmon-enhanced fluorescence (SPFS) for direct analysis of low molecular weight analytes. There will be presented two configurations based on split aptamer and loop aptamer designs for capture of target analyte from analyzed liquid sample. Plasmonic enhancement is reported for direct fluorescence-based reversible assay for adenosine triphosphate (ATP) and thrombin which can serve as biomarkers. An optical configuration of SPFS combined with surface plasmon resonance (SPR) is employed for the investigation of the interaction of loop aptamer with an Alexa Fluor 647 dye attached to its 5' end. The loop aptamer was designed with different spacers in order to control the distance between the gold sensor surface. The specific analyte binding alters the fluorescence signal intensity by a factor as large as 24 by switching the aptamer from "off" to "on" state due to the loop opening. The amplification of fluorescence signal by the resonant excitation of surface plasmons at wavelength that is coincident with the absorption band of the fluorophore increases the measured signal-to-noise ratio and allows real-time observation of affinity binding. The measured distance dependent quenching is compared with simulations in order to identify the optimum combination of distance and fluorophore orientation in the "off" and "on" states. Utilization of aptamer ligands with biocompatible hydrogel-based interfaces for continuous monitoring of low molecular weight analytes will be addressed.

10231-7, Session 2

Wide-field surface plasmon microscopy of nano- and microparticles: features, benchmarking, limitations, and bioanalytical applications

Shavkat Nizamov, Vitali Scherbahn, Vladimir M. Mirsky, Brandenburgische Technische Univ. Cottbus (Germany)

Detection of nano- and microparticles is an important task for chemical analytics, food industry, biotechnology, environmental monitoring and for many other fields of science and industry. For this purpose, a method based on the detection and analysis of minute signals of surface plasmon resonance images due to adsorption of single nanoparticles was developed. This new technology allows one a real-time detection of interaction of single nano- and microparticles with sensor surface. Adsorption of each nanoparticle leads to characteristic diffraction image whose intensity depends on the size and chemical composition of the particle. The adsorption rate characterizes volume concentration of nano- or microparticles. Large monitored surface area of sensor surface enables a high dynamic range of counting and to a correspondingly high dynamic range in the concentration scale. Depending on the type of particles and experimental conditions, the detection limit for aqueous samples can be below 1000 nanoparticles per microliter. Stable analysis of nanoparticles in very complex environment (fruit juice, cosmetic formulations) was demonstrated.

The method can be applied for ultrasensitive detection and analysis of nano- and microparticles of biological (bacteria, viruses, endosomes), biotechnological, (liposomes, protein nanoparticles for drug delivery) or technical origin. Applications in biosensing and bioanalyticas will be discussed.

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10231-8, Session 3

Nanostructure-enhanced surface plasmon resonance imaging

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There remains a need for the multiplexed detection of biomolecules at extremely low concentrations in fields of medical diagnostics, food safety, and security. Surface plasmon resonance imaging is an established biosensing approach in which the measurement of the intensity of light across a sensor chip is correlated with the amount of target biomolecules captured by the respective areas on the chip. In this work, we present a new approach for this method allowing for enhanced bioanalytical performance via the introduction of nanostructured sensing chip and polarization contrast measurement, which enable the exploitation of both amplitude and phase properties of plasmonic resonances on the nanostructures. Here we will discuss a complex theoretical analysis of the sensor performance, whereby we investigate aspects related to both the optical performance as well as the transport of the analyte molecules to the functionalized surfaces. This analysis accounts for the geometrical parameters of the nanostructured sensing surface, the properties of functional coatings, and parameters related to the detection assay. Based on the results of the theoretical analysis, we fabricated sensing chips comprised of arrays of gold nanoparticles (by electron-beam lithography), which were modified by a biofunctional coating to allow for the selective capturing of the target biomolecules in the regions with high sensitivity. In addition, we developed a compact optical reader with an integrated microfluidic cell, allowing for the measurement from 50 independent sensing channels. The performance of this biosensor is demonstrated through the sensitive detection of short oligonucleotides down to the low picomolar level.

10231-9, Session 3

Fabrication of plasmonic nanopore for next generation nanobio sensor device

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There have been tremendous interests about the fabrication of the portable single molecule nanosensor device. The small pocketsize nanobio sensor with the nanopore array on the nanometer thin membrane can be utilized as genome sequencing device with an electrical detection technique. However, the miniaturized portable device manufactured by Oxford Nanopore company is reported to have too high signal to error ratios. This high error could be due to overlapping of the electrical double layer inside the pore channel.

In this report, the optical nanopore on the Au membrane will be reported. Initially, the pyramidal array or flat square array on the (3 mm x 3 mm) square substrate by using conventional Si microfabrication technique was fabricated, followed by deposition of Au membrane using evaporation technique. Then, the the free standing membrane with and without pyramidal structure was obtained by etching the backside supporting film. Prior to electron beam irradiations, the groove patterns were engraved in order to provide the enhanced optical output intensity. Then, Au apertures were drilled with Ga ion Focused ion Beam, and electron beam irradiations were followed. The electron beam induced Au-C membrane was formed under 2 keV 1.4 nA FESEM treatment. The Au clusters were also formed after several months later. Due to melting temperature variation dependent upon the particle size, We observed the inconsistent experimental behavior of the diffused membrane during electron beam treatment by using FESEM or TEM. However, we are able to control the pore size of the Au membrane, either by diffusion technique, or by drilling with focused electron beam at 200 keV. The fabricated pore diameter was measured to be ~ (3 ~ 5)nm, and the smallest pore gap is found to be ~ 0.75 nm by TEM. Controlled nanopore can be utilized as a nanobio sensor device for single molecule analysis such as RNA, DNA, protein, etc.

10231-10, Session 3

Au-based thin film metallic glasses for plasmonic sensor applications

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In this work, we proposed an Au-based thin film metallic glass (TFMG), R55, of which the real part (?r) of dielectric function measured by ellipsometer is smaller than those of Ag and Au for the wavelength smaller than 800 nm. Although the imaginary part (?i) is larger than those of Ag and Au, we could utilize this new material in the plasmonic sensors with sufficiently large propagating surface plasmon resonance (LSPR) and localized surface plasmon resonances (PSPR) in certain wavelength region. Au and Au-based TFMGs with thickness of 50 nm were prepared by the sputtering process on BK7 glass (n = 1.5168) substrate. The substrate was attached to a BK7 prism with index matching oil (n = 1.5150 ± 0.0002). De-ionized water and ethyl alcohol with refractive indexes of 1.333 and 1.361, respectively, were used as analytes in the PSPR measurements. The SPR angle, at which the reflectance in p-direction is minimal in the reflectance intensity versus incident angle curve, shifts with different analytes. The shift angle of Au and Au-based MG thin films for the incident wavelength of 850 nm were 5 and 4 degrees, respectively, as the analyte was switched from de-ionized water to ethyl alcohol. In addition, the adhesion force was measured compared to pure Au film using nano-scratch test, and Au-based TFMG showed stronger adhesion strength than that of Au film, which makes adhesion layer (e. g. Ti) unnecessary in PSPR sensors. The micro- and nano-structures on the surface of Au-based TFMGs for LSPR sensor were

fabricated by embossing stampers onto TFMGs in the super cooled liquid region (SCLR). Then, the stamper was retreated when the temperature was decreased to below 0.8 Tg (glass transition temperature). Using this method, topographic patterns with different shapes and scales could be fabricated. For Raman spectroscopy, the self-assembled molecule of p-aminothiolphenol (p-ATP) was selected as the analyte. Compared with the same structured traditional LSPR sensor of Au (~40 nm in thickness) coated on the top of nano-structured Si substrate, the vibrational characteristic peaks of the analyte for TFMG-based sensor were much more distinguishable as grain boundary scattering did not occur and the vibrational signal of Si at ~900 cm^−1 did not show to overlap the signals of analyte. In conclusion, Au-based TFMGs were verified to be great potential materials for plasmonic sensors, including PSPR- and LSPR-based sensors.

10231-11, Session 3

Investigation of plasmonic transmission in UT shaped graphene arrays

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Surface plasmons (SPs) are excited collective electron oscillations between a metal and a dielectric surface. The graphene shows metallic character at far-infrared and Thz spectral range so it controls and manipulates the light through the excitation surface plasmons. In addition to this it has an advantage lies on its two dimensional character which provides a strong confinement of surface plasmons compare to metals. In this work, we present the optical properties of a graphene plasmonic periodic arrays based on multi-resonant UT shaped structure in the far-infrared and THz regions. The proposed multi-resonant structure shows three different resonance frequencies which can be adjusted not only with geometry of the structure but also with the graphene layers, chemical potential and the relaxation time. The numerical results are calculated by using Finite Difference Time Domain (FDTD) method.

The first and second order resonating modes are located in the U-shaped structure while the third order mode is located in the T-shape. The change in the spectral response is considered for different geometric parameters H (height), L (length), w (width), s (distance between U and T). We mainly focused on the second order mode which has a strong enhancement in transmission compared to the first and third order modes. The second order mode experiences a blueshift when the height and the width of the structure increase. As we increase the length and the distance between U and T, we observe a redshift in the second order resonance mode. We also consider the effect of graphene layers on the transmission. The transmission peak of all three order modes is blue shifted related to increasing number of the graphene layers. The other important parameter for graphene is the chemical potential which is responsible for the surface conductivity of a graphene. All three modes experience a blueshift and the transmission is enhanced at the same time. When we increase the relaxation time of electons, which is strongly related with the chemical potential of the graphene, the second order transmission peak remains unchanged (no red or blue shifted) but the peak becomes sharper.

10231-12, Session 3

Control of plasmonic properties in thermally oxidized gallium nanoparticles for biosensing

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Gallium nanoparticles (NPs) have attracted a lot of interest in the last years for biosensing and photonic devices [1], since they provide a wide tunability of the plasmon resonance energy, from the UV to the IR spectral region. This resonance is controlled by the size, shape, interdistance and the refractive index of the surrounding media [2]. Ga NPs produced by evaporation typically exhibit a hemispherical geometry and, above a critical size, they start to merge and coarsen. When thermally evaporated NPs are exposed to air, a 0.5-3 nm thin layer of an amorphous gallium oxide is formed around the liquid Ga NPs [3] preserving them from the environment and modifying the chemical and biosensing properties.

In this work a thermal oxidation in a quartz tube from 150 ºC to 900 ºC is performed in order to investigate the morphology and structure of the gallium oxide shell. Various involved parameters in the process have been studied such as gas type (argon and oxygen), time, substrate and size of the NPs.

For temperatures between 150 ºC and 300 ºC, we observed a red-shift of the out-of-plane plasmon resonance in spectroscopic ellipsometry ascribed to an increase of the oxide thickness. The increase of the oxide thickness has been also corroborated from X-ray photoelectron spectroscopy. Furthermore, X-ray diffraction shows a decrease of liquid Ga broad bands according to this process. Discrete dipole approximation software has been used to confirm the effects of a shell of increasing thickness on the optical absorption of the nanoparticles. A plastic deformation of the shell is observed by scanning electron microscope evidencing the reduction of the liquid Ga volume in the core of the nanoparticle.

Above 450 ºC, as a consequence of the thermal expansion and vapour pressure of the liquid gallium inside the nanoparticle, the oxide shell breaks and liquid gallium is ejected through a crater as the scanning electron microscope images show. At those temperatures, X-Ray diffraction and cathodoluminiscence demonstrate the formation of good quality crystal ?-Ga2O3.

The functionalization and biosensing properties of the thermally oxidized nanoparticles are investigated and compared with the properties of as-deposited nanoparticles used in our previous works [4].

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10231-13, Session 4

A new concept for noninvasive optical sensing: random lasing

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The development of optical sensing based on radiation-matter "passive" interactions, i.e. based on absorption, scattering, fluorescence and Raman processes, has undergone a large development and are of great interest, due their moderate intrusiveness, in particular for investigating biological samples.

Since '90s, the introduction of working random laser systems [1] has open the new intriguing opportunity to exploit also "active" strategies, e.i. based on amplification of light, in the field of sensing [2,3].

In a nutshell, random lasing occurs in a disordered material with a population inversion if the amplification of the light, during a random propagation, overcomes losses, leading to a laser-like omnidirectional radiation. Indeed, the presence of an optical cavity of the convention laser is substituted by the scattering process, increasing the lifetime of the radiation within the active material that provides the gain by stimulated emission.

A possible application of this topic is the optical sensing, because the striking point is that the spectral characteristics of the emission spectrum strongly depend on the scattering properties of the material [4,5]. Since, in principle, every disordered material can be arranged as a random laser system once gain properties are added, such a kind of radiation has been reported in biological tissues where an active medium is injected [6,7].

The main bottleneck in developing this strategy has been the requirement to alter the sample by injection of external and often also toxic substances.

Here we present a novel concept for a fiber-coupled optical sensor, arranging the system to exploit the disorder of an external and uncontaminated sample for achieving a random laser emission [8]. Such features allow to perform measurement of scattering properties of different samples by using the same non-invasive sensor, suggesting possible future in-vivo applications in tissue optics. The key concept is to concentrate the active properties inside the sensor and to couple the radiation emitted by the active material with the sensor itself after a propagation in the external disordered medium.

The experimental results show that the spectral behaviour of the emission, such as the amplification, the spectral narrowing and the peak wavelength, is extremely sensible to tiny variations in the scattering properties of the disordered sample. Moreover, it has been demonstrated that the same sensor is able to investigate samples that vary by several order of magnitude in the scattering properties.

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10231-14, Session 4

Use of VLC for indoors navigation with RGB LEDs and a-SiC:H photodetector

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Energy saving LED lamps constitutes main elements in Visible Light Communication (VLC) technology as they can be used for communication purposes. Several applications derive from this technology, and indoors positioning is a field where VLC can be used with success, overcoming main advantages related to GPS signals that are strongly absorbed by building infra-structures. Several applications of the proposed technology are predicted, such as guidance of users inside large buildings, location-based services, automation of some inventory management processes, etc..

The work presented in this paper supports the viability of a navigation system based on Visible Light Communication (VLC) for indoors applications. The system design uses RGB LEDs and an a-SiC:H photodetector. The system has four transmission optical channels supplied by the modulation at two different frequencies of the RGB LED internal red and blue chips. Each cardinal direction becomes thus assigned to a specific set of optical excitation, dependent on the wavelength and frequency of the modulated RGB LED.

An optoelectronic characterization of the devices used in the integrated system is presented to support the main results, namely the decoding strategy. The photodetector is a multilayered pin-pin heterostructure based on a-SiC:H on a glass substrate and inserted between two transparent electrical contacts. It works as an optical filter in the visible range, presenting a selective spectral sensitivity dependent on the external optical bias (wavelength, intensity and direction of incidence on the device), that enables the amplification and/or attenuation of specific wavelengths when properly biased with steady state optical illumination.

Each navigation direction is assigned to the presence of 2, 3 or 4 optical signals of characteristic frequency and wavelength. In order to infer the navigation position a dedicated algorithm based on the photocurrent signal measured under front and back bias was developed. First, it is necessary to identify the wavelengths that contribute to the photocurrent signals, which are related to the device wavelength filtering properties. Front biasing is used to detect the red wavelength and back biasing to detect the blue wavelength. Secondly, as signals of the same wavelength may be modulated at different frequencies it is necessary to detect the frequencies present in the output signal, which is done using Fourier analysis.

The viability of the system is demonstrated through the implementation of an automatic algorithm to infer the photodetector cardinal direction. Additional research on the light intensity is presented to investigate the accuracy of the spatial position along a cardinal direction.

A capacitive optoelectronic model supports the experimental results and explains the device operation. A numerical simulation will be presented.

10231-15, Session 4

Coupled data transmission and indoor positioning by using transmitting trichromatic white LEDs and a SiC optical MUX/DEMUX mobile receiver

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The solid-state lighting is revolutionizing the indoor illumination. Current incandescent and fluorescent lamps are being replaced by LEDs at strong pace. Apart from extremely high energy efficiency, LEDs have other advantages such as longer lifecycle and lower heat generation. One additional benefit of LEDs is that they are capable of switching to different light intensity at a very fast rate. This functionality has given rise to a novel communication technology (Visible Light Communication - VLC) where LED luminaires can be used for high speed data transfer. VLC is an attractive replacement for traditional wireless Radio Frequency (RF) communication for an indoor environment. However, VLC is not expected to replace traditional RF communication and is envisioned as an alternative or complementary technology. Due to the combination of illumination and communication, a lot of research has been conducted in VLC applications, such as indoor high speed wireless access and positioning. Indoor positioning based on VLC is a research field that takes advantage of this technology to perform location identification. Its applications cover a wide area where technology can be integrated into consumer-electronics products, such as in-house navigation, which can be used, for instance, to provide location identification and thus guide users inside large museums and shopping malls.

The feasibility of VLC has been both demonstrated by employing Red-Green-Blue (RGB) and phosphor-based LEDs. RGB-LEDs, which compared with phosphor-based LEDs, are more promising solutions to high speed VLC systems, as they offer the possibility of Wavelength Division Multiplexing (WDM), highly increasing the transmission data rate. By employing RGB-LEDs and spectrally efficient modulations, some outstanding achievements on high-speed VLC transmission are possible.

In this paper, we present an indoor positioning system, where trichromatic white LEDs are used as transmitters and an optical processor based on a-SiC:H technology as the mobile receiver. The optical processor is implemented using a double p-i-n photodetector with two UV light biased gates. The relationship between the optical inputs (transmitted data) and the corresponding digital output levels (received data) is established and decoded. An algorithm is developed for the decoding process.

The received signal uses coded multiplexing techniques for supporting communications and navigation concomitantly on the same channel. The device position is estimated using the visible multilateration method through measuring the received signal strength from several non-collinear transmitters. The location and motion information is calculated by position mapping and estimating the location areas. Since the transmitted data of the different LED light sources and its location is known from building floor plans and lighting plans, the corresponding transmitted data information, indoor position and travel direction of the mobile device can be determined.

Results showed that by using a pinpin double photodiode based on a a-SiC:H heterostucture as the receiver and RBG-LED as transmitters, it is possible not only to determine the position of a mobile target but also to infer the travel direction over time, and also the transmitted information received in each position. To improve the transmission rate, parallelized communication will be analysed by using multiple emitters and receivers.

10231-16, Session 4

Interrogation of super-structured FBG sensors based on discrete prolate spheroidal sequences

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We propose, and experimentally validate, an interrogation method to use elaborated structures such as the Discrete Prolate Spheroidal Sequences (DPSS) as sensors. These devices can be accurately manufactured as Super Structured Fiber Bragg Gratings (SSFBG) and therefore retain the same sensing characteristics from FBGs. DPSS structures are a family of codes mutually orthogonal between them. Besides, when manufactured as SSFBG, each device features a distinctive alternating shape embedded into a fixed optical bandwidth, which proves useful when channeling in WDM communications systems. On the other hand, the advantages of encoding FBG sensors were recently demonstrated. More precisely, FBG sensors with a particular amplitude shape, can be interrogated achieving complete identification of each sensor, even under overlapping conditions. Which means that the spectral working range of the sensing network per number of sensors can be reduced since one or more sensors are allowed to share the same spectral region. In a similar approach, we propose to interrogate optical sensors designed as DPSS due to their promising characteristics in encryption for optical communications. Since these devices are more complex structures involving unique amplitude and phase response the demodulating method should be able to recover both amplitude and phase response in order to identify each device in the sensing network. To do so, we propose the use of a tunable, dual–wavelength source (Single Side Band modulation of the tunable laser carrier), sweeping over the working range of the sensors, the reflected signal from the sensors is sent to a Vector Network Analyzer (VNA) in which it is obtained the amplitude and phase ratio between the two reflected wavelengths.

Experimental demonstration has been carried out. With a very good result for the manufacturing of DPSS structures, in the experiments, two DPSS sensors are placed in the same spectral region and one of them is temperature shifted. The correlation, phase and amplitude product, between the original sensor shape and the compounded measurement returns the central wavelength position of each one of the sensors with a proper ratio between the auto correlation peak (ACP) and the cross correlation signal (XC). In this way, feasibility of the interrogation technique for devices involving amplitude and phase distinction has been validated, not only to identify sensors in a measurement network but also to allow overlapping between them. Additionally, a comprehensive comparison between the obtained results and the theoretical simulation is performed. Some interesting figures of merit are studied such as the ACP/XC ratio for each sensor, the scanning time, and the optimum (e reconfigurable) modulation frequency.

10231-17, Session 4

Smart image selection algorithm in analysis plane of the optical-electronic angle measuring sensor

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Optoelectronic sensors are effective instrument for non-contact measurement deformations of such environmentally hazardous facilities like pipelines, fuel reservoirs, power settings and no less effective while verifying the proper installation of the transportation modules, carrying environmentally hazardous substances. The issue of increasing the measuring range of the optoelectronic autocollimation sensor is being considered.

This study presents a fully functional algorithm, based on circle Hough transform which enable to expand the metrological performance of the angle measuring sensor by addressing the problem of malfunction of the device when the marks are overlapping. In order to increase the number of measured angles in autocollimation angle measuring sensor used a control element different from a flat mirror. These control elements increase the number of measured angles and the expense of the small ratio of the optical reduction. However, when such control elements are being used, in the plane of the image analysis may happen marks overlapping which make it impossible to measure the angles.

In order to study the possible solution of this problem, the model for the processing of overlapping arrays of irradiance has been developed and implemented in technology MatLab. This model has allowed investigating the influence overlapping marks on the measuring accuracy of the coordinates. The algorithm is based on the idea using the Hough transform. Hough Transform can solve the problem of grouping boundary points by the use of particular voting procedures to a set of parameterized objects in the image. This is particularly significant when it is necessary to detect objects whose boundaries are crossing. For this purpose, Accumulation array is used for detects the presence of the required object. The dimension of the Accumulation array is equal to the number of unknown parameters of the Hough space. In the case of circular marks, the number of unknowns is equal to three. These will be X and Y, and the radius of the mark. The algorithm is sufficiently flexible and can measure the marks centres while the various parasitic reflections, the inhomogeneity of the background and etc are being ignored. Algorithm determines whether the weight of the boundary at this point is sufficient for each point and its neighbourhoods. This method is based on an assessment of the normal orientation of the voting contour points. The first step of the process is finding edge pixels which are surrounding the perimeter of the object. Evaluation of the amplitude and direction of the gradient vector is used for this purpose. The voting contour point is considered in terms of high modulus gradient. The second step, position estimate and the orientation of the circuit in order to evaluate the center of a circular object of radius R by the movement over a distance R from the edge of the pixel in the direction normal to the contour is being used for each edge pixel.

If this operation is repeated for each edge pixel, a variety of positions alleged points of the centre, which can be averaged to determine the exact location of the centre will be found. After that, algorithm used a threshold filter and search of the local maximum in the accumulator array for determination the centres of the circles.

Application of the proposed algorithm allows to keep the device efficiency when marks are overlapping without significant loss of accuracy. The algorithm passed the functional test.

10231-18, Session 5

GeSn/Ge quantum well photodetectors for short-wave infrared photodetection: experiments and modeling

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Group-IV GeSn material systems have recently considered as a new material for sensitive photodetection in the short-wave infrared (SWIR) region. The introduction of Sn into Ge can effectively narrow the bandgap energies, thereby extending the absorption edges toward the longer wavelengths and enabling effective photodetection in SWIR region. Here we present an experimental and modeling study of GeSn/Ge quantum well (QW) photodetectors on silicon substrates for effective SRIW photodetection. Epitaxial growth of pseudomorphic GeSn/Ge QW structures was realized on Ge-buffered silicon substrates using low-temperature molecular beam epitaxy. Normal incident GeSn/Ge QW photodetectors were then fabricated and characterized. The optical responsivity experiments demonstrate that the photodetection cutoff wavelengths is extended to beyond 1800 nm, enabling effective photodetection in SWIR spectral region. We then develop theoretical models to calculate the composition-dependent strained electron band structures, oscillation strengths, and optical absorption spectra for the pseudomorphic GeSn/Ge QW structures. The results show that Ge1-xSnx

well sandwiched by Ge barriers can achieve a critical type-I alignment at ? point to provide necessary quantum confinement of carriers. With an increase in the Sn content, the band offsets between the GeSn well and Ge barreirs increases, thus enhancing the oscillation strengths of direct interband transitions. In addition, despite stronger quantum confinement with increasing Sn content, the absorption edge can be effectively shifted to longer wavelengths due to the direct bandgap reduction caused by Sn-alloying. These results suggest that GeSn/Ge QW photodetectors are promising for low-cost, high-performance SWIR photodetection applications.

10231-19, Session 5

Compressive spectroscopy by spectral modulation

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We review two compressive spectroscopy techniques based on modulation in the spectral domain that we have recently proposed. Both techniques achieve a compression ratio of ~x10, however each with a different sensing mechanism.

The first technique [1] use a liquid crystal cell as a tunable filter with a single photo detector, where the liquid crystal phase retarder is used to modulate the input spectrum and the photodiode is used to measure the transmitted spectral signal.

The second technique [2] uses a Fabry-Perot etalon as a resonator and a photo-sensor in order to obtain different multiplexed spectral modulation.

In both techniques, sequences of measurements are taken, where each measurement is done with a different state of the retarder or different gap width, respectively. Then, the set of measurements are used as input data to a compressive sensing solver algorithm.

Both techniques have high compressibility ratio and an optical throughput that is at least two orders of magnitude higher than of spectrometers with variable filters. Additionally, these techniques can be extending to work as hyperspectral cameras [3-4].

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10231-20, Session 5

Speckle tracking approaches in speckle correlation sensing

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Laser speckle pattern correlation is a measurement philosophy that uses the translation and decorrelation of recorded laser speckle patterns to infer information about the illuminated object or the illumination source and detector. This approach can be used to measure object translation, rotation and strain[1] and recently there has been increased interest in the technique for practical applications in industry and robotics [2–4].

This paper investigates an alternative data processing method for speckle correlation sensors that mirrors the human approach used in viewing speckle patterns, i.e. identifying characteristic speckles present in both images to determine the speckle shift. Although such feature detection and tracking is a well-developed concept in computer vision their application in laser speckle sensing is limited. To our knowledge, the only prior application of feature matching is the use of the scale invariant feature transform (SIFT) algorithm [5] for personal identification card recognition [6,7] where a feature matching approach is necessary to ensure that speckle patterns can be matched to a database even in the presence of translations and rotations. Such approaches are also potentially well suited to speckle correlation sensing for industrial and robotics applications allowing not only the speckle translation to be determined, but also the rotation of the speckle pattern to be computed.

This paper investigates potential feature detectors and tracking techniques for laser speckle correlation sensing. Initially a range of feature detection methods are reviewed and tested on laser speckle images and their performance assessed. Next, different feature descriptor methods used in the process of matching features between consecutive frames and the processing required to find the translation and rotation from the matched features are described. The performance of these speckle tracking approaches are then investigated and compared with the normalised cross-correlation approach conventionally used in speckle correlation sensing. Results using both simulated and experimental data are shown to be in good agreement for the case of speckle translation. Finally the paper presents preliminary results of the accuracy achievable for object rotation measurements using the feature tracking approach with errors of 0.02° achievable in processing times of around <10ms using simulated and experimental results.

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10231-22, Session 5

Laser imaging through turbid media via speckle correlation

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Optical imaging through turbid media is a difficult challenge. Even a very thin layer of a turbid media, which randomly scatters the probe light, can appear opaque and hide any objects behind it. Despite many recent advances, no current method can image the object behind turbid media with single record using coherent laser illumination. Here we report a method that allows non-invasive single-shot optical imaging through turbid media via speckle correlation. Instead of being as an obstacle in forming diffraction-limited images, speckle actually can be an carrier that encodes sufficient information to image through visually opaque layers. Optical imaging through turbid media is experimentally demonstrated using traditional imaging system with the aid of iterative phase retrieval algorithm. Our method does not require scan of illumination nor two-arm interferometry or long-time exposure in recording, which has new implications in optical sensing through common obscurants such as fog, smoke and haze.

10231-23, Session 6

Analysis of mineral composition by infrared spectral imaging using quantum dot focal plane array sensor

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Infrared (IR) spectral imaging is useful in various fields such as geology, biomedicine, agriculture, and so on. For these applications, high sensitivity, low noise, and high wavelength resolution in wide range of spectrum are required, and quantum dot infrared photodetector (QDIP), having all these features, is considered as a promising candidate. In this report, composition of mineral samples such as conglomerate, sandstone and dolomite are analyzed by IR spectral imaging using the QDIP focal plane arrays (FPAs). The qualitative and quantitative analyses are presented, and the key factor which determines the quantitative precision is discussed.

The conglomerate is composed of gravel-size quartz clasts with a piece of shell fossil (main component CaCO3) on the surface, the sandstone is composed of sand-size quartz clasts with a little limestone (main component CaCO3) mixed on the surface, and the dolomite is composed of calcium magnesium carbonate, ideally CaMg(CO3)2. The emittance spectrum of the mineral composed of CaCO3 has a dip at wavelength of 6.5 ?m, while that of the mineral composed of quartz is almost flat in the same wavelength band. Thus, two types of FPAs having peak-responsivity wavelength at 6.5 ?m (FPA 1) and 5.5 ?m (FPA 2) are used in the experiment.

For the reduction of NETDs, the FPAs are chilled by liquid nitrogen to 77 K, and the noise-equivalent temperature differences (NETDs) of FPA 1 and FPA 2 are 360 mK and 220 mK, respectively. Samples are imaged by a lens of F number 1. To improve contrast between the minerals and the background, the minerals are heated to over 60?.

As the qualitative analysis, the luminance of different components in the rock samples are compared in the image. In the FPA 1 images, the shell fossil in conglomerate and the limestone in sandstone are darker than the other parts of the rocks due to their low emittance at 6.5 ?m. In contrast, the difference in the luminance is hardly observed in the FPA 2 images under the same condition. Therefore, the main component of the mineral has been successfully detected in FPA 1.

As the quantitative analysis, the emittance of dolomite is measured. Ten points in IR image are randomly selected and the average emittance is calculated. The obtained emittances are 0.544±0.012 at 6.5 ?m (FPA 1) and 0.941±0.019 at 5.5 ?m (FPA 2), which means the coefficient of variation of the emittance measurement is ±2.1%-2.2%. As possible sources of the error, four factors in the experiment are considered: precision of a blackbody source for the calibration, precision of a thermocouple for monitoring the temperature of the rocks, the NETD of the FPAs, and fluctuation of room temperature. By calculating the propagation of error, it is found that the precision of thermocouple contributes most significantly (96%) to the total error.

10231-24, Session 6

Analysis of nanoparticles with an optical sensor based on carbon nanotubes

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Nanomaterials play an increasingly important role in science and in every day products. This is due to the varied and specific properties of nanomaterials, whereby especially engineered nanoparticles (ENPs) have shown various beneficial properties for a wide range of applications in consumables [1]. Thus, ENPs have left the scientific laboratories and made their ways into consumer products (e.g. cosmetics, drinks, food and food packaging).

Silver nanoparticles for example are hidden in meat packaging or mitigate body odor via the use in deodorants. The antibacterial effect of silver leads therefore to a high application in consumer products [2].

Apart from their advantages, ENPs are under discussion owing to possible unforeseen hazards and an unknown disposition in living organisms and the environment.

So the question may arise: Are there more benefits or do the harms of ENPs predominate? Unfortunately, this cannot be answered in general. It is highly dependent on specific parameters like the composition, size and shape of ENPs, wherefore a precise identification and characterization is indispensable. All these parameters have to be taken into account for the risk assessment of nanoparticles.

So far, there is a lack of methods, which allow the fast and effective characterization and quantification of such nanoparticles in complex matrices (e.g. creams, fruit juice), since matrix components can impede a specific detection of the analyte.

Therefore, the objective of the interdisciplinary EU-funded project "INSTANT" was the development of a sensor system with an upstream sample preparation for the characterization and quantification of specific nanoparticles in complex matrices using a label free opto-electrochemical sensor array in combination with novel recognition elements. Electrochemical and optical read-out techniques are combined in order to obtain as many of the above-mentioned parameters (e.g. chemical composition) as possible.

As a recognition element, functionalized carbon nanotubes can be effectively used. Owing to their excellent electronical, mechanical and chemical properties, CNTs have already been used for extracting ENPs from complex matrices as sorbent material by filtration [3].

As we worked out, CNTs are an appropriate sensor material for the optical detection of stabilized silver nanoparticles. The project INSTANT, Immobilization results of CNTs on glass transducers, preliminary results of optical measurements with reference nanoparticles and extracted nanoparticles from complex samples are presented within this contribution.

The work was performed as part of the EU-subsidized project INSTANT (FP7-NMP-2007-2013-SME5-280550). The surface modification and the optical measurements were performed in Tübingen. Reference nanoparticles were provided by project partner Federal Institute for Materials Research (BAM). The extraction of nanoparticles was carried out by the group of Prof. Valcárcel from the University of Córdoba. The carbon nanotubes were kindly provided by project partner Nanordic Oy from Finland

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10231-25, Session 6

Oxygen sensing with an absolute optical sensor based on biluminescence

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Organic semiconductors are materials having the benefits of semiconductors together with those of organic molecules. That means, on one hand, these are compounds able to absorb and emit light, as well as conduct electricity to a certain extent, which is enough for the functionality of solid state devices. On the other hand, a remarkable characteristic is that the excitations are typically localized on individual molecules, such that the exchange interactions lead to energetically distinct singlet and triplet states.

According to the spectroscopic selection rules in quantum mechanics, only transitions from the singlet excited state are allowed, deactivating radiatively while generating fluorescence emission in the process, whereas transitions from the triplet excited state are not allowed, because its decay involves a spin flip, and therefore, it is theoretically forbidden by electric dipole transitions. Nevertheless, there is a small probability of these forbidden transitions to occur at a low rate, resulting in a slow radiative deactivation known as phosphorescence emission.

In this context, the property of an organic molecule able to emit light from both their singlet and triplet excited states is called biluminescence. Although this dual state emission, particularly at room temperature, is difficult to achieve by purely organic molecules, it becomes possible if competitive thermal decay is suppressed effectively, allowing emission from the triplet states (i.e. phosphorescence) in addition to the conventional fluorescence.

Here, we have identified biluminescence in simple host:guest systems in which a biluminophore (i.e. organic molecule with biluminescence property) is embedded in an optimum rigid matrix, for example, a combination of PMMA [poly(methyl methacrylate)] as host and NPB [N,N'-di(naphtha-1-yl)-N,N'-diphenyl-benzidine] as biluminophore [Reineke and Baldo, Sci. Rep.]. Such system is unique not only because of the dual state emission, but also the large exciton dynamic range extended up to nine orders of magnitude between nanosecond-lifetime fluorescence and millisecond-lifetime phosphorescence.

In this presentation, we will report on the oxygen sensing characteristics of this luminescent system compared to a benchmarked single state optical sensor. Such properties can be evaluated because of the sensitivity of the triplet state to oxygen and therefore, we investigate the dependence of the persistent phosphorescence on the oxygen content. Furthermore, we will address our efforts towards the potential integration of novel optical biluminescent sensing into organic electronics.

10231-26, Session 6

Long-period grating sensor-based detection of kerosene for monitoring of water contamination: a novel approach

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The improper disposal of kerosene wastes and inappropriate spills from storage tanks are major challenges of marine ecosystem and ground water contamination. Various chemical sensing techniques have been explored for detection of petrochemical contamination at various concentrations ranging from macro level to microscale, however they suffer from certain limitations like cross reactivity, complicated analysis and slow output response. We are proposing a novel optical Long Period Grating sensor anchored with Cu-Metal Organic Frameworks (Cu-MOFs, also known as HKUST-1) for sensitive detection of kerosene at various concentrations. LPG sensors are emerging as potential sensing platforms for chemical and biosensing applications as they possess some unique characteristics like immune to electromagnetic interference, multi parameter sensing feature, cost effective, fast response, low signal to noise ratio and real time monitoring of analytes. A Long Period Grating optical fiber sensor consists of a periodic perturbation of the refractive index of the core which acts as diffraction gratings and light couples from the core mode to set of forward propagating cladding modes of the fibre. This coupling is expressed in the transmission spectrum as a series of loss or resonance bands. The coupling of core mode to cladding mode occurs at phase matching condition and is governed by temperature, strain and surrounding refractive index. Cu-MOFs belongs to Metal Organic Framework family, a subclass of coordination polymers. They represent a promising new class of crystalline solids with ultrahigh porosity, good thermal stability, high surface to volume ratio and tuneable topology and dimensions. They are highly specific to volatile hydrocarbons.

The LPG (grating period: 581μm, grating length: 2cm) was written through point by point technique, subjecting boron co-doped single mode fiber to excimer KrF UV laser having pulse repetition rate of 200 Hz and pulse duration of 15 ns. Peak pulse energy is 3 mJ. Annealing at 150 °C for 24 hours of fabricated LPG sensor is done for thermal stabilization. The Cu-MOFs were prepared by reported standard protocol and formation of blue crystalline frameworks were well confirmed by characterization techniques like SEM and Raman Spectroscopy. The Cu-MOFs were functionalized on silanized cladding surface of LPG sensor by covalent bonding via EDC-NHS crosslinkers. The morphological studies of the functionalized fiber sensor were carried out by optical microscope and SEM analysis. Different dilutions of Kerosene in water were prepared and passed over LPG sensing probe using glass flow cell. After detection of each sample, washing is done thrice with DI water to ensure proper results. Strain and temperature were maintained constant throughout the experiment.

Significant wavelength shifts were noted for all kerosene samples with Cu-MOFs functionalized LPG sensing probe. Detection up to micro level has been experimentally demonstrated and significant wavelength shift of 809 pm was observed for 0.01μl/ml concentration of kerosene in water.

10231-27, Session 7

Discrimination of trace nitroaromatics using linear discriminant analysis on aerosol jet printed fluorescent sensor arrays

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Due to increasing security concerns, the demand for explosives detection technologies has grown significantly to ensure the safety of civilians worldwide. It has been shown that nitroaromatic explosives can be efficiently detected by optical methods such as fluorescence quenching (FQ) [1]. Here, the transduction is typically based on an electron transfer mechanism. Detection limits in the range of sub parts-per-billion have been reported in literature for thin film sensors [2]. This renders FQ as a very attractive approach for chemical trace vapor sensing [3]. However, the identification and quantification of various target analytes is required in many applications. Here, one of the major challenges is the fabrication of sensor arrays with a low in-batch variation. Therefore, reproducible sensor arrays need to be developed enabling the discrimination of such trace vapors using patter recognition methods [4].

In this work, we report on fluorescent sensor arrays fabricated by aerosol jet printing on glass substrates to detect explosives-related nitroaromatic species. The printed sensor arrays were made of six different fluorescent polymers responding to nitroaromatic vapors through a photo-induced electron transfer resulting in a quenched fluorescence proportional to the vapor concentration. Distinct FQ patterns were detected for nitroaromatic species including nitrobenzene, 1,3-dinitrobenzene and 2,4-dinitrotoluene. The detected fingerprints were evaluated at low concentrations of only 1, 3 and 10 parts-per-billion in air. Linear discriminant analysis (LDA)

was used to train each sensor array enabling the discrimination of the target analyte vapors. To investigate the in-batch variation for a given sensor array, the measured FQ patterns from the other arrays were used to benchmark the LDA by predicting the target analytes and vapor concentrations. On average, we report low in-batch misclassification rates of about 6 – 11 % indicating excellent discriminatory abilities at low concentrations close to the detection limits. Furthermore, the fabrication based on digital printing potentially enables the realization of low-cost fluorescent sensor arrays in high volumes towards the reliable detection of trace explosives.

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10231-28, Session 7

Infrared sensor for water pollution detection and monitoring

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Development of Mid-infrared sensors is a challenge of great importance for the detection of biochemical molecules. Mid-infrared range (4000 – 400 cm-1) contains the absorption bands related to the vibrations of organic molecules (nitrates, hydrocarbons, pesticides...). Chalcogenide glasses are an important part class of amorphous materials appropriate for sensing applications. Indeed, they are mainly studied and used for their wide transparency in the infrared range (2 – 15 ?m for selenide glasses) and their high refractive index (between 2 and 3). The aims of this study are to synthesize and characterize chalcogenide thin films for developing mid-IR optical waveguides.

For this study, chalcogenide glasses with composition $(GeSe_2)_{100-x}(Sb_2Se_3)_x$, where x=5, 10, 20, 30, 40, 50, 60 and 70 were prepared. Among these compositions, two bulk glasses were chosen for their mid-IR transparency, stability against crystallization and their refractive index contrast suitable for mid-IR wave-guiding. The two compositions were used for RF magnetron sputtering deposition. The study of the influence of different sputtering parameters (Ar pressure, RF power and time deposition) on thin films characteristics (chemical composition, deposition rate, surface roughness, refractive index in near-IR and mid-IR and band-gap energy) by an experimental design allows controlling the structure of the optical waveguide. Micro-patterning of the guiding layer and light injection efficiency experiments in near-IR and mid-IR were performed. Finally, optical waveguide surface was functionalized by deposition of a hydrophobic polymer, which enables detection of organic molecules in water (sea water, wastewater and groundwater).

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10231-29, Session 7

A robust and reliable optical trace oxygen sensor

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In applications of nitrogen generation, industrial gas manufacturing and food packaging there is a need to ensure oxygen (O2) is absent from the environment, even at the lowest concentration levels. Therefore, there has been an increased growth in the development of trace O2 parts per million (ppm) sensors over the past decade to detect and quantify the concentration of molecular O2 in the environment whether it be dissolved or gaseous O2.

The majority of commercially available trace O2 sensors are based on electrochemical, zirconia and paramagnetic technologies. Electrochemical sensors are low in cost, small, accurate and have a reasonable operational lifetime but they suffer from long recovery times and deplete when exposed to ambient O2 thus calibration and/or replacement is required periodically. Zirconia and paramagnetic sensors offer greater operational lifetimes and calibration is less frequent but they are expensive and in the case of zirconia, they require a lot of power due to their high temperature of operation.

Here, the development of a luminescence-based optical trace O2 sensor is presented. Luminescence-based sensing is now regarded as one of the best techniques for the detection and quantification of O2. This is due to the high detection sensitivity, no O2 is consumed and there are a vast array of luminescent indicators and sensing platforms (polymers) that can be selected to suit the desired application.

Due to the non-depleting principle of luminescence it will be shown that the sensor responds reversibly and is highly repeatable when exposed to ambient O2, an advantage over traditional electrochemical sensors. The patented sensing formulation which we employ allows for a robust and stable sensor. In addition, the sensor can operate over a relatively wide temperature range (-30 to +60 °C) and detects O2 in the 0–1000 ppm range and/or the partial pressure of oxygen (ppO2) from 0–1200 μBar. This is achieved through an extensive calibration process in which the miniaturised device comes equipped with temperature and pressure sensors to compensate for these environmental variables during calibration. The long-term stability of the sensor will be presented along with the drift characteristics, a phenomenon most sensors display which ultimately determines the operational lifetime of the sensor. Taking all the environmental factors into account has allowed us to develop a new optical O2 sensor which has a much improved performance for the low O2 concentration marketplace.

10231-30, Session 7

Pocket size pH reader system using smart phone and fluorescent indicator array

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A library of 13 (3-ethyl-2,4-dimethyl)-boron-dipyrromethene (BODIPY) fluorescent pH-indicator dyes and 3 reference dyes has been synthesized.

The library has been carefully designed to yield probes, the dynamic sensing range of, which covers the complete pH scale in water. Additionally, the design also considered to produce dyes with similar excitation and emission windows together with high ON-OFF intensity switching to simplify the read-out of the library.

The optical properties of the dyes were found to be in line with those of related BODIPY dyes published previously, which implies good photostability and high brightness.

The dependence of their optical properties with the pH has been thoroughly characterized. For that, pH-sensing studies have been carried out using a) water:EtOH solutions of the dyes at different pH and b) pH measurements in water using strips coated with polyurethane based hydrogel mixtures containing the pH indicators. From these studies it has been concluded that the fluorescent dyes are able to accurately respond to pH changes in water solutions as well as embedded in the hydrogel.

After proving the correct operation of the hydrogel sensors, a system to read the pH response of the library on a smart phone was developed, utilizing a 3D-printed smart phone case containing all the necessary optical components for excitation and fluorescence collection.

In a further step toward application, a 4x4 element matrix containing the different hydrogel solutions of the pH dyes on a poly(methyl methacrylate) strip has been prepared to facilitate introduction into the smart phone cover after having been dipped into a test solution. Once inside the cover, the sensor spots are excited with visible LED light and the fluorescence is collected by the smart phone's CCD after filtering off the reflected LED light. An automatic mathematical analysis of the collected image is performed next by a smart phone application. After the analysis, the actual pH of the solution is provided as an on-screen result.

Different tests showed a very good agreement of the measured values for those observed with a glass pH electrode, with uncertainties below ± 0.16 pH.

Finally, additional experiments demonstrated the reversibility and reusability of the system.

10231-31, Session 8

Active optical remote sensing (AORS) sensors/instrumentations for NASA's future Earth science missions *(Invited Paper)*

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NASA is at fore-front in developing active optical remote sensing technologies and unique capabilities towards space-based observations for understanding the complexities and interactions among Earth system components. Advancing Active Optical Remote Sensing (AORS) technologies and techniques are critical for NASA to move into the next logical era of laser remote sensing by enabling such critical space-based measurements as winds, ozone, CO2, clouds, aerosols, surface topography, ice thickness, vegetation, trace atmospheric species, biogenic traces gases and materials, as well as oceanic properties. AORS uniquely provides for high vertical resolution measurements of these parameters in the Earth and science arenas. AORS enables several key measurements that are likely to open new frontiers of research that cannot be obtained any other way.

10231-32, Session 8

Monolithically integrated arrays of 3D microtubular vertical ring resonators on photonic waveguides for optofluidic applications

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A novel platform for optofluidic applications is realized by monolithic integration of an array of ultra-compact three-dimensional (3D) vertically rolled-up microtube ring resonators (VRU-MRRs) with polymer waveguides. The on-chip integrated system is realized by rolling up 2D differentially strained TiO2 nanomembranes into 3D microtubular cavities on a nanophotonic chip and seamlessly overlaid over several integrated waveguides. Whispering-gallery modes are observed in the telecom wavelength range, and their spectral peak positions shift significantly when measurements are performed while immersing the tubes or filling their hollow cores with water, thus manifesting a compact, robust all-integrated optofluidic microtube ring resonator with a high functionality, and well suited for dense multiplexing of sensors. In this intriguing vertical transmission scheme, optical characterization of the air filled integrated VRU-MRRs reveals an extinction ratio as high as 32 dB, which is the highest, recorded for an integrated VRU-MRR to date. In the case of solution-filled VRU-MRR, the maximum extinction ratio of this integrated system is as high as 10 dB due to the strong absorption of water at telecom wavelengths. Thus, this change in the transmission spectrum of the VRU-MRRs represents a novel sensing methodology in addition to using spectral mode shifts. The achievement of this work opens up fascinating opportunities to realize massively parallel optofluidic microsystems with exceptional multi-functionality and flexibility for analysis of biomaterials in lab-in-a-tube systems on a single chip.

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10231-33, Session 8

Black silicon n-type photodiodes with high response over wide spectral range

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Silicon photodiodes are used as in vast field of applications ranging from automotive twilight detectors to medical imaging. When illuminated, they generate an output which is proportional to light level with excellent linearity over several decades of light intensity. As a first approximation within their typical range of use, when used in photovoltaic mode without bias, one electron is released per incoming photon having energy exceeding silicon bandgap.

However, in practice all of these charges can't be collected as the performance of photodiodes is limited by both reflectance of incoming light and recombination of generated charges before they get collected to external circuit. The most important recombination modes are surface recombination on the (top) surface and auger recombination in doped region forming the diode pn-junction. Methods of effective passivation have been developed to reduce surface recombination and junction doping profile and anneal processes have been optimized to reduce auger recombination, but there's plenty of room for improvement. Various antireflective layers have been implemented to reduce the reflectance but they are typically optimized to some wavelength range at the cost of reduced response at other wavelengths.

To overcome these limitations, photodiodes were developed with very low reflectance by using black silicon, combined with excellent atomic layer deposited (ALD) aluminum oxide surface passivation to reduce surface recombination, and removing the junction doping altogether by using induced junction for charge collection thus avoiding auger recombination. Sample photodiodes were manufactured in the facilities of Micronova Nanofabrication Center in Espoo, Finland on high resistivity n-type wafers. Both electrical and optical properties were characterized. The devices were shown to behave in general like pn junction photodiodes do.

External quantum efficiency, that is, the amount of charge collected and recorded compared to the amount photons entering the device surface (from air) exceeds 96% over the whole measured wavelength range of 250 to 950 nm and over 100% in wavelengths below 300 nm. This is a

very good result taking into account that external quantum efficiency includes losses due to reflection. Reflectance of the samples was also measured and was well below 1%. Due to known uncertainties of spectral range measurements using reference diodes, these results were confirmed by extremely precise laser calibration measurements at VTT Technical Research Centre of Finland Ltd, Centre for Metrology MIKES. The external quantum efficiencies recorded were 96,4% at 488 nm, 96,5% at 633 nm and 96,4% at 933 nm. These results should be compared to typical general purpose wide spectral range diodes that typically reach about 80%, and even less towards shorter wavelengths (violet to ultraviolet).

Such high quantum efficiency photodiodes can potentially be utilized in applications where losses are significant, like for example various calibration purposes. One example of potential applications is Predictable Quantum Efficient Detector. The authors are now proceeding towards verifying applicability of this diode structure to medical imaging. Achieved improvement in detector quantum efficiency would help reduce patient radiation dose for certain image quality, or to improve the image quality that can be reached with a certain acceptable dose.

10231-35, Session 8

Low-temperature oxidation in air of iron thin films monitored with long-period fiber gratings

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Corrosion of iron and its alloys is the degradation of material properties due to interactions with their environments. Civil and military infrastructures, along with countless commercial products are made of iron, steel or alloys containing iron. The exploration of land and sea resources, such as agriculture, aquaculture and land or sea mining, requires metallic structures, often made of iron alloys, which are exposed to corrosion. Corrosion causes unwanted use of resources, contamination of industry products, reduction in efficiency, compromise safety in civil structures and imposes expensive maintenance. Its consequences led to large economic losses. In 2013, the direct cost of corrosion was ~3% of U.S.A. gross domestic product (GDP).

The characteristic properties of long period fiber gratings (LPFGs) depend on coupling light into propagating cladding modes which gives rise to the presence of attenuation bands in the transmission spectrum. The evanescent field of the cladding modes extends to the surrounding medium enabling refractive index measurements.

Optical fiber sensors based on LPFGs have been extensively studied and applied as strain, bending and temperature sensors, in the detection of inorganic and biological compounds. Real time monitoring of oxidation of pure metals in air was reported by measuring the wavelength shift and the optical power variation of the LPFGs attenuation band. LPFGs coated with metal oxides with specific properties leads to wavelength sensitivity enhancement when comparing to bare LPFG.

In this work, is presented an investigation of LPFGs over coated with different thicknesses of iron (Fe) and subjected to oxidation in air atmosphere under controlled temperature and humidity. The formation of iron oxides was monitored in real time by following the features of the LPFGs attenuation band. Iron was deposited simultaneously on top of silicon substrates for further morphological analysis by scanning electron microscope and energy dispersive X-ray spectroscopy (SEM/EDS). Preliminary results show that iron coated LPFGs can be used as sensors for early warning of corrosion in projects where metal structures made of iron alloys are in contact with atmospheric air.

10231-36, Session 8

Surface plasmon resonance prism coupler for enhanced circular dichrosim/birefringence sensing

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A novel method for surface plasmon resonance (SPR) enhanced circular dichroism (CD), circular birefringence (CB), and degree of polarization (DOP) detection is proposed using Stokes-Mueller matrix polarimetry technique. The validity of the analytical model is confirmed by means of numerical simulations, and the simulation results show that the proposed detection method for CB and CD has a sensitivity of 10-5 RIU and 10-4 RIU (refractive index unit) for refractive indices in the range of 1.3-1.4, respectively. The practical feasibility of the proposed method is demonstrated by the experimental results for detecting the CB/CD/DOP with the glucose-chlorophyllin compound samples contained polystyrene microsphere particles. It is shown that the extracted CB value decreases linearly with glucose concentration over the considered range while the extracted CD value increases linearly with the chlorophyll concentration over the considered range. In general, the results obtained in this study show that the measured CB and CD response is highly sensitive to the polarization scanning angle. Consequently, the potential of Stokes-Mueller matrix polarimetry for high-resolution in CB/CD/DOP detection is confirmed.

10231-21, Session PS

The research of the possibility of the dispersion method sensitivity increase for the air tract vertical temperature gradient determination by analyzing the diffraction pattern

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The accuracy of modern optoelectronic systems of spatial positioning, which are based on the reference marks coordinates determination, is always limited by uncertainty caused by the optical radiation propagation in a heterogeneous environment - air tract. One of the main sources of error in this case is the presence of the vertical temperature gradient, that changes the direction of the optical radiation in the vertical plane. There is a method for determining the vertical temperature gradient, based on the air tract dispersion. In this method, the photodetector detects the radiation of red and blue spectral range emitted from one optical radiation source. According to the difference of the image energy centers coordinates in the blue and red range y1 and y2, respectively, there is a possibility to indirectly determine the value of vertical temperature gradient along the well-known formula. There is a realization of the dispersion method where the photodetector is a commercially-produced camera with a color matrix photodetector, made by Bayer pattern. In this case, the analysis of the radiation in the blue and red range is carried out simultaneously and independently by signal software separation into components corresponding to the red and blue elements of the Bayer pattern. This approach is quite promising, as it combines an optical-electronic control channel and a compensator of an error introduced by the presence of the vertical temperature gradient. The disadvantage of the dispersion method is its low sensitivity to small values of the temperature gradient. For example, the difference in image energy centers in the red and blue spectral range at the measurement distance z = 100 m and a value of the vertical temperature gradient ?Ty = 0.01 C°/m is 0,006 pixels (with a pixel size of 2,2x2,2 microns) and commensurate with the standard deviation of the image energy center vertical coordinates in the absence of the temperature gradient, that is caused by a sensor noise.

In this paper, we study ways to increase the sensitivity of the dispersion method for determining the vertical temperature gradient, implemented on commercially-produced camera with a color matrix photodetector,

analyzing the diffraction pattern. The essence of this method consists of decomposing the incoming radiation on the optical system into a set of diffraction minima and maxima with a specially installed at the lens entrance pupil slit. The difference between the energy centers coordinates of the side maxima in this case will be much greater than the difference registered in the absence of the diffraction slit. Thus, with the coordinates of the energy centers of the side maxima and their order relative to the central peak may be at a much lower error to determine the magnitude of the vertical temperature gradient, even if its value is small. Simulation of the diffraction method is carried out in a software environment for optical systems calculating Zemax. The analysis of the diffraction pattern is conducted without regard to the aberrations of the optical receiving system.

10231-34, Session PS

Acoustic waves in tilted fiber Bragg gratings for sensing applications

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Tilted fiber Bragg gratings (TFBGs) are one of the most attractive kind of optical fiber sensor technology due to their intrinsic properties. On the other hand, the acousto-optic effect is an important, fast and accurate mechanism that can be used to change and control several properties of fiber gratings in silica and polymer optical fiber. Several all-optical devices for optical communications and sensing have been successfully designed and constructed using this effect. In this work, we present the recent results regarding the production of optical sensors, through the acousto-optic effect in TFBGs. The cladding and core modes amplitude of a TFBG can be controlled by means of the power levels from acoustic wave source. Also, the cladding modes of a TFBG can be coupled back to the core mode by launching acoustic waves. Induced bands are created on the left side of the original Bragg wavelength due to phase matching to be satisfied. The refractive index (RI) is analyzed in detail when acoustic waves are turned on using saccharose solutions with different RI from 1.33 to 1.43.

10231-44, Session PS

Vacuum temperature field simulation and experiments of four-mode differential laser gyroscope

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In order to reduce the influence of temperature in a vacuum on four-mode differential laser gyroscope (FMDLG), the temperature field model is established with the finite element software ANSYS, and the temperature field in a vacuum are emulated. Firstly, the finite element model is simplified, and then the disposal of the material parameters, the calculating methods of the heat generation rate and forced convective heat transfer coefficient in gain area of He-Ne mixed gas are developed. At last, the steady temperature field and the transient temperature field of one hour and two hours are given. The highest and lowest temperature regions and the distribution of the temperature gradient are simulated. The results are compared with the experimental tests and the maximum error is less than 0.82? which validate the rationality of the finite element model. This research can provide some help to select temperature testing points and improve the effect of the temperature compensation for the FMDLG in a vacuum.

10231-45, Session PS

Influence of the substrate layer and fixation materials for measuring the deformation of a standard telecommunication fiber G.652.D with a distributed system BOTDR

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Article deal of the problematic of impact fixing optical fiber for measuring the deformation with the distributed system known as Brillouin Optical Time Domain Reflectometry (BOTDR). The measurement principle of BOTDR system based on scanning of Brillouin frequency. The analysis focused on monitoring changes Brillouin frequency for various bends and size of the substrate layer in combination with different types of fixing materials. We used distributed system DiTEST STA-R Omnisense. For the analysis was used a standard telecommunication optical fiber G.652.D. Deformation of the optical fiber was carried out by bending at a special tool. This article aims to find the most suitable method of implementing a fiber-optics for practical applications. It showed that it is necessary to pay attention to the size of the substrate layer and the fixing material to optimize the sensitivity in the measurement of mechanical deformations and the forces.

10231-46, Session PS

Analysis of the detection materials as resonant pads for attaching the measuring arm of the interferometer when sensing mechanical vibrations

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Fiber-optic sensors (FOS) today among the most widespread measuring sensors and during various types of measuring are irreplaceable. Among the distinctive features include immunity to electromagnetic interference, passivity regarding power supply and high sensitivity. One of the representatives FOS is the interferometric sensors working on the principle of interference of light. Authors of this article focused on the analysis of the detection material as resonant pads for attaching the measuring arm of the interferometer when sensing mechanical vibrations (low frequencies). A typical example is the use of interferometer sensors in automobile traffic while sensing a vibration response from the roadway while passing the cars. For analysis was used a sensor with Mach-Zehnder interferometer. Defined were ten different detection materials about constant size and thickness, we analysed the influence on the sensitivity and frequency range of the interferometer. Based on the results we were defined the best material for sensing mechanical vibrations. In the case of this material, we analysed the influence of different thickness on the sensitivity and frequency range of the interferometer. The signal was processed by applications created in LabView development environment. The results were verified by repeated laboratory testing.

10231-47, Session PS

Analysis encapsulation of fiber Bragg gratings into polydimethylsiloxane for the needs of dynamic weighing

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Authors of the article focused on the possible encapsulation method of fiber Bragg gratings (FBGs) for the needs of dynamic weighing. The article describes the influence of various shapes, sizes and quantity of PDMS on the strain sensitivity of FBG sensor. Measurements were carried out under laboratory conditions. For monitoring the parameters, we used broad-spectrum light source LED (Light-Emitting Diode) with a central wavelength of 1550 nm and optical spectrum analyzer with sampling rate 4 kHz. For encapsulation of FBGs was chosen specific material polymer polydimethylsiloxane (PDMS). A characteristic feature of this material is very high mechanical resistance, chemical resistance and temperature stability in the range of values -60 °C to + 200 °C. The combination of characteristic advantages of optical fibers (electromagnetic immunity) with stated properties of PDMS gives us the innovative type of encapsulated sensor which could be used for example for the needs of dynamic weighing in worsened or potentially hazardous conditions. This type of monitoring weighing is fully dielectric.

10231-48, Session PS

Photovoltaic optical sensors for high-power conversion and information transmission

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Utilization of fiber-optic lines not only for information transfer but also for electric supply is a point of scientific and practical interest in recent years [1]. The following advantages exist at energy transport by means of high-power laser beaming through fiber lines:

– ideal isolation suppressing galvanic link between the energy source and consumer, absence of noise disturbances at radio frequencies (RF) and immunity to exterior RF noise;

– lightweight cable compared to a copper one;

– high chemical resistance to a corrosive medium, chemical and electrochemical stability;-

– low metal consuming cable.

Therefore this approach becomes attractive for different robotics applications and autonomous units used in critical environmental conditions.

The best electrical-to-optical and optical-to-electrical conversion efficiencies were achieved using semiconductor AlGaAs/GaAs laser sources and GaAs photovoltaic converters. Efficiency values recorded for AlGaAs/GaAs lasers (wavelengths of 808–830 nm) were as high as 60 %. Building an array of such sources allows to rise optical power up to 1 kW [2]. Efficiency of GaAs photovoltaic converters exceeds 50 % at steady-state laser illumination [3].

Using a fiber-optic line for both energy supply and information transmission needs to apply technologies of space division multiplexing (SDM) or wavelength division multiplexing (WDM). In the first case two fibers are used to transfer power and information separately what impairs utilization of the medium. In the second case two signals differs in the wavelength. On the receiver end they are splitted by means of interference filters. Disadvantages of the WDM are additional power losses in filters and problems with optical elements ageing at high power densities of light which lead to reduction of an overall system efficiency.

To improve efficiency and reliability of the fiber-optic line an optical sensor for direct conversion of high-power modulated laser radiation can be used. This sensor has to extract both information and power-transmitting signals. However, to the present date achieved efficiencies and power rates on such type of photovoltaic converters are considerably low [4].

In the current work investigated were the opportunities of conversion of the modulated laser radiation with mean power of 20 dBm or higher using optical sensors based on p-n AlGaAs/GaAs and n-p GaInP/GaAs with multiple photovoltaic cells, providing acceptable efficiency values at optical-to-electrical conversion.

An equivalent circuit for the sensors has been developed and their characteristics were simulated using SPICE-based program. Studied were the modes of the laser radiation modulation. It was shown that the best efficiency values can be achieved using pulse-width modulation (PWM) of the laser source. Analyzed was a novel variance of PWM which could be applied for the double-junction photovoltaic sensors. The method is based on using two wavelength-splitted sources and detection of an information signal through photocurrent mismatch of the sensor's subcells. A prototype of such photovoltaic sensor has been designed on the base of GaInP/GaAs heterostructure and its characteristics were investigated. With using of the developed model the sensor power conversion efficiency exceeding 36 % at information rates up to 100 MBd was demonstrated.

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10231-49, Session PS

Autocollimation sensor to control the angular deformation with increased measurement range

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During the installation and operation of large-scale objects, need to use angle measurement devices, such as optical-electronic autocollimator sensors, which allow to control the deformation of objects. The reasons for such deformations are own weight structures, as well as external weather conditions. After considering the optical-electronic autocollimator sensors on the market, can conclude that these autocollimator sensors have insufficient measurement range (up to 5 meters), one of the reasons of the limited distance is error due to vignetting of the reflected beam, because with increase in the measurement range, accuracy of the measurement is reduced, because there is no means of compensating beam vignetting. For the solution of this problem, effectively use optoelectronic sensors with two main basic schemes: autocollimation and autoreflection. The autocollimation system have larger sensitivity than autoreflection ones. Although, the autoreflection system have larger measurement range than autocollimation system and it is more effective for using of infrared emissions diodes as sources and at usage of matrix charge-coupled devices as photo-receiver. The autoreflection system allows measuring a mirror turning angle as sensitive element in a point of angular deformation with a potential accuracy up to 0.05 arc. sec. Actually the error can exceed considerably the specified value because of existence of systematic error, one of which main components is the error owing to vignetting of a working beam. The reason of vignetting error is changing of irradiance distribution of the image on the autocollimator analyzer owing to cutting of a bundle of optical beams at a mirror deviation in case of angular deformation.

The component of systematic error due to vignetting of the beam can be eliminated in case of existence of the analytical description of changes in irradiance distribution of the analyzed image. Because of the complexity of the analytical description of the vignetting processes proposes the

use of computer models. The modelling is based on approximation according to which each point of the finite image of a source of radiation essentially is the focused area of intersection of the entrance pupil and the elementary beam reflected by a mirror, and its energy is proportional to integral (the general energy) on this area.

For the analysis of vignetting we defined static characteristics of the analyzer for different coefficients of vignetting image. Based on the received dependence for compensation of systematic error due to vignetting is equal 30 arc. sec, it is practically possible to realize measuring accuracy close to the potential.

As this systematic measurement error unacceptably large, there is a need to compensate for this error. For the design of the algorithm compensate for systematic error were considered three cases of displacement vignetting field on a matrix analyzer due to the rotation of control element: 1) displacement of vignetting area is small; 2) displacement of vignetting area equal to half the size of the image; 3) displacement of vignetting area more than a half the size of the image. After using the compensation algorithm, the error due to the vignetting amounts to a negligible value 0.4 arc. sec.

Using a computer analytical modelling to image processing on a matrix CCD was investigated systematic error due to vignetting. The designed algorithm compensation systematic error due to vignetting allows increasing the measurement range of the autocollimation sensor in 1.7-2 times.

10231-50, Session PS

Rydberg atom-based RF field measurements: spectroscopy of cesium Rydberg atoms in strong radio-frequency fields

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Atom-based field measurement has made significant progress in reproducibility, accuracy, and resolution. Rydberg atom, principal quantum number n>>1, has applications in electrometry due to their large dc polarizabilities and microwave-transition dipole moments, which follow scaling laws ~n^7 and~ n^4, these properties make Rydberg atoms extremely sensitive to dc and ac electric fields. In this work, we present an atom-based, calibration-free RF field measurement.

In the presentation, we investigate Rydberg atoms modulated by the strong radio-frequency (RF) fields with a frequency of 50-100 MHz. The Rydberg atoms are prepared in a room-temperature cesium cell, and their level structure is probed using electromagnetically induced transparency (EIT). The EIT spectra involved Rydberg three-level system is used to measure the rf-induced ac level shifts and sidebands.

The experiments are performed in a room-temperature cesium cell. The relevant atomic levels, cesium atom ground state (6S) and excited state (6P) and Rydberg state (nS), form a three-level system. A weak probe laser (852 nm) is resonant with the transition from ground state 6S to excited state 6P, while a strong coupling laser (510 nm) scans through the Rydberg transition from excited state 6P. The coupling laser induces an increased transmission for the probe laser when an EIT double-resonance condition is met. The EIT signal is observed by measuring the transmitted power of the probe beam with a photodiode detector. Rydberg level is modulated with the RF field with a frequency tens of MHz, producing field-mixed Rydberg levels with modulation sidebands. The experimental results demonstrated that in the weak-field regime, the ac shift of the main EIT line is observed, whereas in the strong-field regime, rf-induced modulation sidebands and complex state mixing and level crossings with high hydrogenlike states can be obtained. The phenomenon is simulated and analyzed using Floquet theory and agree well with the experimental observations. Our results show that all-optical spectroscopy of Rydberg atoms in vapor cells can serve as an atom-based, and calibration-free technique to measure rf electric fields and to analyze their higher-harmonic contents.

10231-51, Session PS

Detection of trace amount of NO2 gas using tunable blue laser diode

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Nitrogen dioxide, one of the main air pollutants, has strong light absorption cross section in the blue region of the optical spectrum. Recent availability of blue laser diodes provides possibility of detecting NO2 in open-air paths with very low detection limits. However, in the blue region, the sharp features of the NO2 spectrum is relatively broad with typical width of tenths of nanometer. This poses a serious challenge for implementing traditional direct or wave-modulated tunable diode laser absorption spectroscopy. In this study, we report the usage of a blue laser diode with multi longitudinal modes tuned over about one nanometer in detecting trace amount of NO2 gas. Details of the setup and its optimization will be presented along with a comparison of its performance with other NO2 detection optical methods.

10231-53, Session PS

A high resolution hand-held focused beam profiler

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The shape of a beam is important in any laser application and depending on the final implementation, there exists a preferred one which is defined by the irradiance distribution 1. The energy distribution (or laser beam profile) is an important parameter in a focused beam, for instance, in laser cut industry, where the beam shape determines the quality of the cut. In terms of alignment, the energy distribution also plays an important role since the system must be configured in order to reduce the aberration effects and achieve the highest intensity. Nowadays a beam profiler is used in both industry and research laboratories with the aim to characterize laser beams used in free-space communications, focusing and welding, among other systems. The purpose of the profile analyzers is to know the main parameters of the beam, to control its characteristics as uniformity, shape, beam size, and also to align the lenses with respect to the laser system. In this work is presented a high resolution hand-held and compact design of a beam profiler capable to meassure at the focal plane, with covered range from 400 nm to 1000 nm. The detection is reached with a CCD sensor sized in 3673.6 ?m x 2738.4 ?m which acquire a photograph, of the previously attenuated focused beam to avoid the sensor damage, the result is an image of the beam intensity distribution, which is digitally processed with a Raspberry™ module gathering significant results such as beam waist, centroid, uniformity as well as some aberrations. The profiler resolution is 1.4 ?m and was tested and validated in three different systems whose implementation was based on a focused beam. The spot sizes measurements were compared with the Foucault knife-edge test.

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10231-54, Session PS

Simulation and research of the gamma-ray detectors based on the CsI crystals and silicon photomultipliers

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Scintillator based detectors are widely used for gamma-rays, which are applied for experimental physics and for radiation monitoring, in industry, radiobiology and medicine.

Traditionally the detector device includes scintillation crystal and photoelectronic multiplier (PM). This traditional device has excellent characteristics of sensitivity but not always appropriate for field application. In last case the unit should be strong, and the traditional photomultipliers are fragile and rather delicate to provide long life cycle. Additionally the traditional PM has rather big size.

The novel photodetectors like silicon photomultipliers (SiPM) can help to solve both problems of big sizes for field devices and fragility, they are durable and relatively small. In given case traditional PM is located in contact with the scintillation crystal, but for SiPM this variant is not optimal.

When we should detect separate scintillations, the signal is low. In this case when we place SiPM on the exit side of the scintillation crystal in contact with the exit face of the crystal it may lead to large error in signal measuring because the signal on the separate SiPM area will be strongly dependent on the scintillation location. For example, if the scintillation is close to the exit end of the crystal and we use array 2 x 2 of SiPM we can see that the signal on one of the elements of the array is much higher for that array which is closer to the scintillation location. In that case the measuring error will be rather high. So optimal case is when we have as uniform light distribution on the SiPM as possible for all scintillation locations.

In the work we consider the case of using lightguides of different configuration and analyze the uniformity of signals of the SiPM array of 2 x 2. For modeling the light distribution we use Zemax software in Non-Sequential mode. The models used are described and the results of modeling are also given.

10231-55, Session PS

Evaluating inner surface roughness of inline/picoliter fiber optic spectrometer fabricated by an NUV femtosecond laser drilling

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In this study, we have evaluated inner surface roughness of in-line/pico-liter fiber optic spectrometer fabricated by an NUV femtosecond laser drilling. It has been demonstrated that microholes were fabricated into commercial available glass fiber optics without breaking off. The microhole works as in-line/pico-liter fiber optic spectrometer. The spectrometer has capability of measuring refractive index of liquid sample. The attractive feature of the spectrometer is very small sensing volume which has several tens of pico-liter. A second harmonic 400 nm femtosecond laser with 350 fs pulse duration launched onto the glass fiber optic. After 100 pulse shots with 30 uJ of pulse energy, an optical inner surface quality of microhole was acquired. A characteristic of high transmittance was obtained using the microhole with the optical inner surface quality. The optical inner surface quality of microhole was verified by measuring the transmittance of 94% of infrared light emission launched from superluminescent diode. Although a high aspect ratio of the microhole was fabricated after 1000 pulse shots, there was inner surface roughness. In order to control the inner surface roughness, the repetition rate was changed 10 to 1000 Hz. In all the cases of repetition rates, the inner surface roughnesses were occurred. It was confirmed that ablated fused silica particles deposited on the inner surface of microhole during femtosecond ablation. The depth of microhole was deepened with 1 kHz of repetition rate. In comparison to 10 Hz, the depth of microhole was increased by approximately 75% in the case of 1 kHz. It was assumed that heat accumulation effect enlarged the length of drilling during femtosecond processing. From the results, to minimize inner surface roughness, this is the best method to use low number of laser shots. Minimization of inner surface roughness improves light transmission characteristics of in-line/pico-liter spectroscopy at the region of shorter wavelength. The optical inner surface quality of microhole facilitates modification of nanomaterials onto its surface.

10231-56, Session PS

Autocollimation sensor for measuring the angular deformations with the pyramidal prismatic reflector

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The most promising type sensors of angular deformations are autocollimation optic-electronic systems in which pyramidal prismatic reflectors are used. The using of pyramidal prism as element sensor of the angular rotation instead the traditional flat mirror allows to measure the angular deformation in three orthogonal axes. The rotation around horizontal axis is the pitch angle and rotation around vertical axis is yaw angle. The deformation around view line is the roll angle. The autocollimation sensor with prismatic reflector uses this three angle of deformations.

In this paper the two variants for creation the autocollimation sensor with the pyramidal prismatic reflectors are considered.

First prismatic reflector has the value of the dihedral angle with deviation from 90 degrees: ?=ϖ/2+?. For this variant of the autocollimation sensor the incident beam is parallel to the optical axis of the autocollimator objective.

Second prismatic reflector is made with small pyramidal ?. For this variant unit vector of normal to the refracting faces makes an angle ϖ/2+? with unit vector of the prism rib. The incident beam is non-parallel to the optical axis of the autocollimator objective.

For definition of the angular spatial position object, the optic-electronic angular measuring autocollimators are effectively used. They include actually autocollimation block with the channels of radiation and reception beam of optical radiation and control element. Control element establishes on the object and sensitives to rotations of object. The receiving channel of autocollimators determines change angular position of the beam, which is generated on matrix analyzer by radiating channel after reflection from control element.

The autocollimation sensor with the quadrangular pyramidal prismatic reflectors with angle at the vertex is 90 degrees is consided.

When measurement of the bitch and yaw angles, the necessary diameter of objective for these two reception beams is 1.41 times less than for reception beam is reflected from flat mirror at the same angles of rotation.

For measurement of the roll angle one of the equivalent prism BR-180 constituent pyramidal reflector (e.g., with rib is parallel to the yaw axis) is performed with the dihedral angle with small deviation ? from 90 degrees.

In the result of the computer simulation the functional ratio between value of unit vector components reflected beams and the value of the measured angles ?1, ?2, ?3 as pitch, yaw and roll of deformation is found. The rigorous algorithm for measuring the three angular rotations is found. Measuring error of the pitch and yaw angles ?1, ?2 and roll angle ?3 for the second variant of prismatic reflector is less relatively the first variant of configuration. However, the algorithm of measurement for second variant is more complicated, because it misses ability of initial issuance reflector with zero angles of rotation due the asymmetry of the spot of processed images on matrix analyzer of autocollimators. This circumstance allows to recommend the pyramidal reflectors with deviation of the dihedral angle for three-axis autocollimation sensors.

10231-57, Session PS

Multiagent robotic systems' ambient light sensor

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Ambient light sensors are widely used in robotics. But speaking about swarm robotics, the technology which has great number of specific features and is developing, we can't help mentioning that its important to use sensors on each robot not only in order to help it to get directionally oriented, but also to follow light emitted by robot-chief or to help to find the goal easier. In the paper the authors try to explain the role of ALS and how it can be used to provide swarm robots information security.

To the approach, which is proposed for evaluating of SRS IS characteristics, are made following general scientific and specific demands:

• general scientific: objectivity, reproducibility, sensitivity, stability (either in terms of statistical stability or in the sense of "indestructibility" of approach applied to the class of mentioned systems);

• specific: performance realized as the possibility of obtaining adequate characteristics within established limits (time, financial, human etc).

The main directions of implementation of these requirements are general science practice:

• application of proven scientific-methodological research machine;

• orientation on taken in scientific community standarts, recommendations and best practices;

• proved input of limitations and admissions.

Thus, the main goal of the paper is to develop the approach for assessing of the selected by the researcher IS characteristics of SRS and/or essentially depended on level of IS and meet report requirements.

10231-58, Session PS

Optical choppers with rotational elements: modeling, design and prototypes

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We present an overview of our contributions regarding the analysis and development of optical choppers. Their applications range numerous domains, from optical sensing in radiometry or telescopes to laser manufacturing and biomedical imaging – for example for the controlled attenuation of light, the elimination of selected spectral domains, or switching of optical paths. While these aspects are briefly pointed out, the paper focuses on our analysis, modeling, and manufacturing of prototypes for choppers with: (a) wheels with windows with linear margins; (b) wheels with windows with non-linear margins (semi-circular, elliptical, or with other curved shapes), outward or inward; (c) rotational shafts with different shapes, with slits or with holes. While variant (a) represents classical choppers, variant (b) represents the "eclipse" choppers that we have developed and also patented for the solution with two adjustable wheels that produces circular windows. Variant (c), of choppers with shafts is also a patent application. Their transmission functions are discussed, for the shape of the laser pulses produced and for the attenuation coefficients obtained. While this discussion has been completed analytically for top-hat laser beams, it has been modeled using simulations for Gaussian and Bessel beams. Design, manufacturing, and prototypes of the different chopper configurations complete the presentation. Selected References: [1] Duma V.-F., Theoretical approach on optical choppers for top-hat light beam distributions, Journal of Optics A: Pure and Applied Optics, 10(6), 064008 (2008); [2] Duma V.-F., Optical choppers with circular-shaped windows: Modulation functions, Communications in Nonlinear Science and Numerical Simulation 16(5), 2218-2224 (2011); [3] Duma V.-F., Prototypes and modulation functions of classical and novel configurations of optical chopper wheels, Latin American Journal of Solids and Structures 10(1), 5-18 (2013); [4] Duma V.-F., Nicolov M. F, Mnerie C., Szantho L., Optical modulator with rotation movement, Romanian Patent RO 126505/2016; [5] Duma V.-F., Demian D., Optical modulator, has solid rotating shaft with some through slots of well-defined profiles, Romanian Patent number RO129610-A0, Derwent Primary Accession Nr: 2014-P50842 (pending).

10231-59, Session PS

Optical signal processing for smart vehicle lighting system using a-SiCH technology

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We propose the use of Visible Light Communication (VLC) for vehicle safety applications, creating a smart vehicle lighting system that combines the functions of illumination and signaling, communications, and positioning.

We use the nonlinear property of SiC multilayer devices under UV irradiation to design an optical processor uniquely positioned to help developing automated vehicle technologies that enable cars to communicate with the environment around them. This environment can be other cars and trucks, traffic lights, roadworks or even pedestrians and cyclists. The automated driving framework includes a high definition map which provides precise latitude/longitude positioning on the road surface. The safety system could either send a warning to the driver or automatically lower the speed in advance, decreasing the severity of a potential collision or even avoiding it. By using Visible Light Communication (VLC) between vehicles, drivers are given a clearer knowledge of the preceding and nearby vehicles status, including their heading, speed, location, as well as information as to whether the drivers are stepping on their brakes. These aspects can significantly reduce the chance of traffic accidents. When coordinating the speed of the vehicles in the same lane, the technology can also eliminate unnecessary variation of the distance between consecutive vehicles that causes the traffic shockwave, increasing the road capacity to avoid traffic congestion.

The system is a self-positioning system in which the measuring units are mobile. Each vehicle is assumed to be equipped with two headlamp transmitters, two side light mirrors transmitters, and two taillight transmitters. Distance receivers are assumed to be placed at the front, at the back and at each of the two side mirrors. Trichromatic Red-Green-Blue LEDs (RGB-LED) are used together for illumination proposes and individually, each chip, to transmit the channel location and data information. The chips of the RGB-LEDs can be switched on and off individually, in a desired bit sequence to transmit the information. The receivers consist of two stacked amorphous cells [p(SiC:H)/i(SiC:H)/n(SiC:H)/p(SiC:H)/i(Si:H)/n(Si:H)] sandwich between conductive transparent contacts. The receivers join the simultaneous demultiplexing operation with the photodetection and self-amplification. The information and the code position of each LED are transmitted simultaneously through the RGB pulsed transmitted channels. A violet LED is used for error control. Free space is the transmission medium. An on-off code is used to transmit data. A visible multi-lateration method estimates the position of the device by using the decoded information received from several, non-collinear transmitters. To improve the transmission rate, parallelized communication will be analysed by using multiple emitters and receivers.

The proposed coding is based on SiC technology. Furthermore, we present a way to achieve vehicular communication using the parity bits and a navigation syndrome. A representation with a 4 bit original string color message and the transmitted 7 bit string, the accurate positional information encoding/decoding and the design of SiC navigation syndrome generators are discussed and tested.

10231-60, Session PS

Refractive index sensor based on multimode plastic optical fiber with long period grating

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Recently, the refractive index (RI) sensors based on plastic optical fibers (POFs) have attracted much attention of researchers. Compared with glass optical fibers (GOFs), the POFs are now widely recognized to offer some unique advantages, such as better flexibility, larger diameter, higher numerical aperture, easier handling and lower attenuation in the visible region. Due to the multimode characteristic, POFs based sensors are more suitable for intensity modulation scheme. With special focus on the low cost solution, the RI sensors based on POFs can be considered as a valuable alternative to those based on GOFs.

It is well known that the RI sensitivity could be enhanced by modifying the structure of multi-mode POFs in some ways, such as side-polishing, tapering, making a hole, and so on. Therefore, in this work we tried to a new approach to modify the structure of POFs for increasing the RI sensitivity. A long period grating was fabricated on the surface of the POF by a simple die-press-print method using a commercial available thread rod as the mould. The RI sensing performances for straight and macro-bending (U-shaped) POFs with the long period gratings were studied. It is found that the straight RI sensing probe with long period grating structure was not sensitive enough for RI measurement. After bending the straight POF probes with long period grating into U-shaped probes, the RI sensing performance was improved markedly. By altering the structural parameters, the RI sensing performances of the U-shaped POF probes with long period grating structure were optimized, and a sensitivity of 1130%/RIU in the RI range of 1.33-1.41 was obtained. The probe is a low cost solution for RI sensing purpose, which has the features of simple structure, easy fabrication, compact size and intensity modulation at visible wavelengths.

10231-61, Session PS

Novel techniques for optical sensor using single core multilayer structures for electric field detection

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This paper studies the effect of the electrostriction force on the single optical dielectric core coated with multi-layers based on whispering gallery mode (WGM). The sensing element is a micro-sphere made off polymeric material coated with multi-layers having different electric and mechanical properties. The external electric field deforming the sensing element causing shifts in its WGM spectrum. The multi-layer structures will enhance the body and the pressure forces acting on the core of the sensing element. Due to the gradient on the dielectric constant; pressure forces at the interface between every two layers will be created. Also, the gradient on Young's modulus will affect the overall stiffness of the optical sensor. In turn the sensitivity of the optical sensor to the electric field will be increased when the materials of each layer selected properly. A mathematical model is used to test the effect for that multi-layer structures. Two layering techniques are considered to increase the sensor's sensitivity; (i) Dielectric constant layering technique and; (ii) Young's modulus layering technique. In the first technique, Young's modulus is kept constant for all layers, while the dielectric constants are varying. In this technique, results show that the highest sensitivity achieved when the layers are arranged in an ascending order. In the second technique, Young's modulus is varying along the layers, while the dielectric constant has a certain constant value per layer. On the other hand, the descending order will enhance the sensitivity in the second technique. Overall, results show the multi-layer sphere based on these techniques will enhance the sensitivity compared to the typical polymeric optical sensor. Preliminary experiments proved that the bandwidth of the multi-layer structures for the optical sensor will also be improved compared to the typical one.

10231-64, Session PS

Green upconversion fluorescence temperature sensor based on erbium-doped phosphor

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Temperature sensing based on fluorescence intensity ratio (FIR) technique has received much attention recently [1]–[4]. The FIR technique compares the rare earth ions fluorescence intensities of two temperature dependent emissions from two closely spaced energy levels to a lower state, such as Er3+, Pr3+, Yb3+ and Nd3+ [5,6]. In Er3+ ions the two upconversion emissions 4S3/2 ?4I15/2 (550 nm) and 2H11/2?4I15/2 (530 nm) are particularly suitable for this application. This is because the 4S3/2 and 2H11/2 states are closely spaced and the intensities of the two emissions are temperature-dependent. Also, a 980 nm laser diode (LD) can be used as the pump source, and this excitation wavelength is desirable for biological applications since auto-fluorescence in biological tissues is absent at this wavelength. For certain applications, such as microelectronic circuits, biological tissues and in vivo cells, micro- and nano- sized materials that can be used as temperature sensors are attractive.

We have reported optical temperature sensors based on ErNbO4 and Er2O3.3Nb2O5 phosphors [7,8], and showed that for a simple structure that consists of a 980nm pump LD, two narrowband filters and two Si photocells, the thermal response of the Si photocell shows a near linear dependence on temperature, the linearity is independent of input power, and the sensor exhibits a relative sensitivity of ~ 5-7 ? 10?3 K?1 within the temperature range of 303-353 K. In this work, we studied the temperature characteristics of Er(NbO3)3 phosphor mixed with potassium bromide (KBr), and the KBr: Er(NbO3)3 molar ratio was varied from 0:1 to 100:1. The results confirm the enhancement of fluorescence intensity and increased temperature sensitivity, and the relative sensitivity is increased by 14%.

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10231-65, Session PS

Construction, laboratory test of the fiber optic rotational seismograph FOSREM for rotational seismology area of interest

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A relatively young field of study named Rotational Seismology caused highly interest in the investigation of rotational movements generated by earthquakes, explosions, and ambient vibrations. It includes a wide range of scientific branches. In order to continue the exploration of new findings regarding Rotational Seismology one needs to apply appropriate rotational sensors which should fulfill the following technical requirements: absolute insensitivity to linear motions as well as an opportunity to measure the linear and rotational motion separately; compactness and stable in respond to the surrounding conditions; equipped with independent power supply; wide range of the measurements: amplitude 10e-8 rad/s (tele-seismic distances) – 10e0 rad/s (near seismic source); frequency 10e-3 Hz – 10e2 Hz.

The presented in this work system works by measuring Sagnac effect and generally consists of two basic elements: optical sensor and electronic part. The optical sensor is based on so-called the minimum configuration of FOG where the Sagnac effect produces a phase shift between two counter-propagating light beams proportional to the measured rotation speed. The main advantage and attribute of such kind of sensor is its

complete insensitivity to linear motions and a direct measurement of rotational speed. It may work even when tilted, and moreover, it may recording the tilt if is used in continuous mode.

The electronic system, involving specific electronic solutions, calculates and records rotational events data by realizing synchronous detection in a digital form by using 32 bit DSP. Storage data and system control are realized over the internet by using connection between FOSREM and GSM/GPS. Its advanced and innovative design enables to measure a component of the rotation in the wide range of signal amplitude from 2?10e-8 rad/s up to 10 rad/s, as well as in the wide frequency band from DC to 328.12/n Hz (n=1, ..., 128). Its relatively small dimension (360x360x160 mm) and remotely controlled electronic module makes FOSREM portable and autonomous device.

Moreover, authors have adapted a simple seismic table, which allows to generate real horizontal shakes which occur during earthquakes, for rotational sensors testing. The obtained data suggest that the FOSREM is suitable for Rotational Seismology research as well as engineering application. The carried out measurements included the Allan variance noise analysis confirmed the extremely advanced technical solutions as well as wide possible application field like seismic monitoring in observatories, buildings, mines and even on glaciers and in their vicinity.

10231-66, Session PS

CO2 sensing at atmospheric pressure using fiber Fabry-Perot interferometer

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A fiber Fabry–Perot interferometer (FPI) for CO2 gas sensing at atmospheric pressure is proposed and experimentally demonstrated. The gas sensing material is poly(ethyleneimine) (PEI)/ Poly(vinylalcohol) (PVA) compound, which exhibits reversible refrative index change upon absorption and release of CO2 gas molecules. The FPI is fabricated by coating a PEI/PVA film with a thickness of 15?m film at the end face of a single-mode fiber (SMF). A well-confined interference spectrum with fringe contrast of 19.5 dB and free spectra range (FSR) of 33.15 nm is obtained. The proposed FPI sensor is sensitive to the CO2 gas concentration change, and a sensitivity of 0.2833nm/PCT is obtained. The FPI sensor provides a potential solution in the development of low-cost and compact gas sensors for CO2 leakage monitoring.

10231-67, Session PS

Measuring the modulation-transfer function of radiation-tolerant machine-vision system using the sum of harmonic components of different frequency

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Nuclear energy is one of the most important sectors of global energy industry, that has been making a significant contribution to the electricity generation for several decades already.

There are special robotic systems to maintain the basic technical processes at the nuclear power plants, which are intended for long time operation without breaking in high radiation environment.

To ensure the necessary safety level in robotic systems that are used for nuclear power plant maintenance and to allow the operator to control the systems actions, the machine-vision systems are applied. There are special requirements for the radiation tolerance, image quality and automation of the machine-vision systems.

One of the main characteristics of the machine-vision system is its resolution, which is generally measured by determining the impact of the system on the special test pattern.

The most often used test images for resolution measurement are: bands groups having an equal width, sinusoids groups of different frequencies, slanted edge of high or low contrast, random target pattern (printed or displayed at the screen) and speckle pattern, generated by laser source and diffuser.

To show the resolution of the machine-vision system at different spatial frequencies one can use modulation transfer function, which describes the spatial frequency response of the system transfer from the object area to image area, using the sinusoids with different frequencies.
The advantages for using modulation transfer function as the general characteristic to measure resolution are: the ability to measure image quality directly and quantitatively, the minimal impact of the human factor (measurement is objective), the ability to measure the quality of combined systems (different components of the system, such as eye, lens, image detector can be reduced to one characteristic).

The source test pattern can also have brightness, that changes harmonically in a certain direction, e. g. along the image line. For the linear image transmission system final image brightness will also change harmonically in corresponding direction. Both harmonic components are related by modulation-transfer function, so the modulation-transfer function value will depend on spatial frequency and the brightness changing of the source test pattern.

In this paper we describe the procedure of determining the number of values of the modulation transfer function using the sum of the harmonic components of the relationship of the source test pattern brightness on the spatial coordinates. The measurement can be done in two directions: meridional and sagittal by rotating the source test pattern.

10231-68, Session PS

Nematic liquid crystal device based on biconical optical fiber taper

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In recent years, a certain number of experiments has been undertaken to connect optical fibers and liquid crystals materials. In many cases Such hybrid devices were made as a filling in air hole of photonic crystal fibers. The other possibility was performing a guidable cladding on an optical fiber taper. All above approaches use liquid crystal properties which allow to change refractive index value by reorganizing of molecules orientation induced by electric field. Depending on obtained refractive index value it can be also changing the modes of propagate light beam.

Tapering process allows to change optional boundary condition of fibers and to interact directly with the propagating light beam. The theoretical and experimental investigations of changing core and cladding diameters, mode field diameter as well as distribution of refractive index profile along the taper structure show that there is many option for manufacturing advanced elements for sensor application. Light beam which leaks out of the taper structure is susceptible to external materials which can be characterized by a variable state of concentration. In this work we have presented an investigation of the opportunity to use nematic liquid crystals (NLC) mixture 1550C1 as a tunable cladding in fiber sensor systems based on a biconical optical fiber taper. The construction of a liquid crystal cell which allows to place the taper waist region between two substrates with ITO layers has been developed in the Institute of Applied Physics MUT, Warsaw, Poland. To obtain very good properties of the manufactured device minimization of attenuation of individual elements should be obtained. The base element – a biconical optical taper was made on Fiber-Optic Taper Element Technology arrangement which was developed in the laboratory. For manufacturing the device, along type taper with the elongation equal to 30.50±0.16mm. The diameter of waist region was below 10.0±0.5?m. The manufactured taper posses very low insertion losses equal to 0.18±0.02dB. The measurement of the manufactured NLC taper device is divided into three parts. Device was measured in the wide range of wavelengths between 500 - 850 nm given by Fianium supercontinuum source as well as in narrow band from 532 nm laser. NLC was stimulated with different modulation 1Hz, 30Hz as well as without modulation. Applied external electric field was in the range 0-160V. Obtained results show a very good fast answer of device to external disturbance. Transmission characteristics in a wide range was observed by OSA. Additionally, the device was put to the test of temperature in the range of 20oC to 80oC, which scope liquid crystals change a structure from nematic to isotropic liquid.

10231-69, Session PS

Experimental study of laser-trimmed surface acoustic wave delay line topologies

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Nowadays popularity of sensors based on surface acoustic waves (SAW) is rising. These sensors are comparable with MEMS in size, price and sensitivity characteristics, but also include such unique advantages as high shock resistance and possibility of a wireless sensing. Formation of electrode topology on a surface of a wafer is a key part of SAW-based sensor fabrication process and mostly determines its sensitivity characteristics.

Originally, a photolithography method is used for electrode topology creation. However, modern design concepts of solid-state inertial sensors (gyroscopes, accelerometers) have complicated topology that may contain several delay lines, resonators and other elements on a single wafer. Production of a photo mask for its etching is a difficult and expensive process. It becomes crucial in case of small series that are needed at the development stage for optimization purposes – every small change in topology requires a new photomask. In addition, a life cycle of these masks is comparatively short. Therefore, a method of drawing a sensitive element topology using a high-precision laser seems perspective. The essence of proposed method is to evaporate unneeded material from a fully metallized wafer, leaving only desired topology. In this case, there is no need to produce a photo mask. Thus, it is possible to change sensing element configuration without any essential expenses of time and money that will allow simplifying technological process of SAW-based sensors production.

To estimate possibilities of described method a number of delay lines was produced and tested. At the first stage, two low frequency (13 and 16 MHz) delay lines with a 400 nm metallization were created using a precise fiber-optic laser. Parameters of these delay lines were investigated and were found in a close match with desired values. At the second stage, delay lines with a thick (5 ?m) metal films were produced with a single and double-sided topologies. Results of its experimental tests are to be presented.

10231-70, Session PS

The influence of the whispering gallery modes resonators shape on their sensitivity to the movement

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The whispering gallery modes resonators are axially symmetrical resonators with smooth edges, supporting the existence of the whispering gallery modes by the total internal reflection on the surface of the resonator. For today various types of such resonators were developed, namely the ball-shaped, tor-shaped, bottle-shaped, disk-shaped etc. The movement of whispering gallery modes resonators in inertial space causes the changes of their shape. The result is a spectral shift of the whispering gallery modes. Optical methods allow to register this shift with high precision. It can be used in particular for the measurement of angular velocities and linear accelerations in inertial orientation and navigation systems. However, the whispering gallery modes resonators have cross axes of sensitivity in addition to the main axis. When measuring the parameters of motion the orientations of the rotation axis and acceleration axis generally are unknown. This leads to uncertainty of the measurement results. This work is devoted to the study of the influence of the whispering gallery modes resonators shape on the sensitivity to the movement of their main and cross axes.

10231-71, Session PS

Design of an optical sun sensor for a space application: a reliable passive sun tracking device for the SOLAR/SOLSPEC instrument

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SOLSPEC is a spectroradiometer measuring the UV-VIS-IR solar irradiance from 166 nm to 3088 nm. It is part of the instruments composing the SOLAR payload mounted on the zenith external platform of the European Columbus module of the International Space Station (ISS), since February 2008. Solar flux is received by the instruments of the payload (SOLSPEC, SOLACES and SOVIM) thanks to the Coarse Pointing Device (CPD) composing the guiding system of the SOLAR platform. A complementary Sun position tracking module, the Position Sensitive Device (PSD), is also integrated to SOLSPEC. The PSD is a passive instrument designed to determine the Sun's position. It has no feedback on the CPD and therefore no influence on the payload orientation. It uses a wide band-pass glass filter centered on 501 nm to attenuate the solar flux. The amount of dielectric coating on the surface of the glass was precisely tuned taking into account the amount of estimated solar flux to be attenuated in orbit. The solar image is formed with a Cook's configuration lens-triplet into a photodiode resistive surface, generating photocurrents in four terminals. By weighting these photocurrents, the Sun's image position on the detector's surface is accurately detected. The PSD module has been a useful tool to monitor for alignment offsets between the CPD and the SOLAR payload. A misalignment produced during the pre-flight integration between CPD and the SOLAR payload was monitored and quantified in orbit. The PSD is used in all SOLSPEC's solar mode operations mode to monitor the quality of the Sun tracking of SOLSPEC as well of the SOLAR payload. The PSD is also used in the criss-cross operational mode. In this mode the CPD is intentionally depointed for a range of angular positions. In this mode it is possible to monitor for SOLAR/SOLSPEC's 3 spectrometers (UV, VIS, IR) angular responses in orbit.

We first give a detailed description of the PSD's optical design and functionalities. We then present some results of the PSD data analysis. We will show that the PSD module has, despite operating in a severe spatial environment as it is the ISS environment (outgassing, vehicles), preserved its full potential from 2008 up to now thanks to its design and appropriate selection of components. We conclude that its robustness makes of the PSD module a simple, yet reliable, instrument useful for future long-term space missions.

10231-72, Session PS

Temperature sensing setup based on an aluminum coated Mach-Zehnder Interferometer

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In this paper a temperature sensing setup based on a Mach-Zehnder Interferometer (MZI), coated with aluminum is proposed. Here, this interferometer is fabricated through fusion splicing. It is formed by the concatenation of two endings of Single Mode Fiber (SMF) with a segment of Photonic Crystal Fiber (PCF) between them. The first splicing is the SMF-PCF interface, and acts as beam splitter, causing the excitement both the core and cladding modes of the PCF. In the second splicing, the PCF-SMF union, couple again these modes into the core. Here both PCF cladding and core modes interfere with each other, this interaction results in an interference pattern as the output signal of the system, which is observed with an Optical Spectrum Analyzer. For the fabrication of the interferometer a commercial fusion splicer Fitel S175 was used, with the following characteristics: 91 mW arc power, 240 ms of prefusion time, and 860 ms of arc duration. The SMF is conventional plastic SMF-28 fiber. Moreover, the PCF has 6 hollow cavities around the core, each one of 6.48

µm of diameter and 1 µm average separation between them. The core's diameter is 5.48 µm, this segment has a length of 7 cm and was coated with a thin layer of aluminum through the evaporation technique. Surface plasmons are waves that propagate along the surface of a conductor. By adding a thin metal layer to the PCF section, a new mode appears in form of this phenomenon, and enhances the performance of the device. A temperature control based on thermoelectric Peltier cells and Infrared detectors was used for the experimental setup. The device was characterized in a temperature range from 25 ºC to 43 ºC. Experimental results show that placing the metal coating, a visibility of 16 dB and sensitivity of 0.25 nm/ºC can be obtained. The proposed structure is simple, cost effective, robust and easy to fabricate.

10231-73, Session PS

Shack-Hartmann wavefront sensor using a Raspberry Pi embedded system

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In this work we present the design and manufacture of a Shack-Hartmann wavefront sensor using a Raspberry Pi and a microlens array. The main goal of this sensor is to recover the wavefront of a laser beam and to characterize its spatial phase using a simple and compact Raspberry Pi and the Raspberry Pi embedded camera. The recovery algorithm is based on a modified version of the Southwell method and was written in Python as well as its user interface. Experimental results and reconstructed wavefronts are presented.

10231-74, Session PS

Splicing and shaping of the special optical fibers

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We present development of new methods and techniques of the splicing and shaping optical fibers. We developed new techniques of splicing for standard Single Mode (SM) and Multimode (MM) optical fibers and optical fibers with different diameters in the wavelength range from 532 to 1550 nm. Together with development these techniques we prepared other techniques to splicing and shaping special optical fibers like as Polarization-Maintaining (PM) or hollow core Photonic Crystal Fiber (PCF) and theirs cross splicing methods with focus to minimalize backreflection and attenuation. The splicing special optical fibers especially PCF fibers with standard telecommunication and other SM fibers can be done by light adjustment of our developed techniques. Adjustment of the splicing process has to be prepared for any new optical fibers and new fibers combinations. The splicing of the same types of fibers from different manufacturers has to adjust too. We are able to splice PCF with standard telecommunication fiber with attenuation up to 1 dB. The method is also presented.

In the next step we developed techniques to tapering optical fibers. We are able to made optical tapers from ultra-short called adiabatic with length around 400 um up to long tapers with length up to 6 millimeters.

Development of these new techniques and methods of the optical fibers splicing are made with respect to using these fibers to another research and development in the field of optical fibers sensors, laser frequency stabilization and laser interferometry based on optical fibers. Especially for the field of laser frequency stabilization we developed and present new techniques to closing microstructured fibers with gases inside.

10231-75, Session PS

Optical fiber sensors preparation

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We present development of the new technology to preparation of the fiber optic sensors with Fiber Bragg Gratings (FBG). We prepared complete technology from design of the sensor properties, the calculation of the demanded properties of FBG, calculation phase mask properties to writing FBG, processing of phase masks by e-beam lithography, preparation optical fibers to writing FBG through prepared phase mask and writing FBG in to the optical fibers. At the end we are able to prepare complete housing for the realized optical fiber with FBG in dependence on the physical parameters measurement and on the place of the measurement. We present separate parts of the whole technology.

The technology of processing and measurement of the sensors to measurement strain and temperature is presented in the next step. These sensors were prepared for the structure health monitoring. We focused our set up to prepare sensors to mounting and measure existing buildings and critical infrastructures. The data from measurement of the nuclear power plant Temelin containment shape deformation are presented. We used standard FBG reflection wavelength measurement by our developed measurement system with tunable optical filter. The other principle measurement we used to set up and measure our vibration sensors. The sensors contain FBG in tapered optical fiber. In this case we can measure only the optical power, which depends on the angle of the fiber with FBG behind the taper. The FBG is written into the fiber under defined angle with respect to axis of light propagation. The parameters of the sensors measurement in depend on different tapers and the different angles are presented.

10231-76, Session PS

The using of fiber-guided multichannel pyrometer for diagnostics of laser aided metal deposition with gas-powder jet

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The way of further industrial implementation of additive manufacturing technology is the applying of the on-line control in laser machining. The optical method of pyrometry provides the tool to analyze the evolution of surface temperature versus laser operation parameters and materials properties to improve the quality and increase the productivity of the technology process [1-2].

However, there are some problems to apply the pyrometry in laser machining, for instance, there is the difficulty of determining the temperature distribution in a small heating regions of the order of (1...2) mm and less [3]. And there is also the problem of determining the true temperature from the luminosity of the melt and solidified metal due to the dependence of the luminosity factor on a number of uncontrollable factors, such as kind of material, the temperature, the surface condition, the location of the surface relative to the pyrometer sensor [4].

The use of optical fiber bundle in the optical path of the multi-channel pyrometer of the spectral ratio allowed us to diagnose thermal conditions in the region of the formation of a metal bead during the processes of laser aided metal deposition with gas-powder jet. The results of measurements of local thermal luminance dynamics of molten and solidified metal are given for the case of 10.6 mkm radiation of the 1.2 kW CO2 laser is focused to a spot diameter of about 1 mm. We used powders of stainless steel similar to grades 304 and 316 in experiments.

Lined-up end faces of the optical fibers were located at the place of formation of the thermal luminosity spot image by the focusing lens of the pyrometer (F=63 mm, material CaF2). There were used five optical channels of the pyrometer in the measurement series. The near IR luminance from the region of about 60 µm were transmitted with low loss through each of the five fiber channels and enlighten the two-color sensor. [5]. Fibers with an inner diameter of 50 µm were located at a distance of 0.3 mm from each other. The sampling frequency of temperature data in each channel was 40 kHz.

The dependences of temperature changes in the five areas of the bead formation regions on the scanning speed, laser power and powder flow rate are shown. The possibility of the surface temperature monitoring through a stream of metal powder is demonstrated in the case of spectral ratio pyrometer application. The using of optical fiber bundle has allowed us to enhance the spatial sensitivity and spatial selectivity of the temperature measurements by multichannel pyrometer.

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10231-77, Session PS

Plasmonically-enhanced fluorescence for biosensor applications

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The detection of low concentration of analytes in is an important task in diagnostic applications. Fluorescence spectroscopy provides an established means for detection of molecular analytes by using assays with fluorophore labels. To further improve the sensitivity, such assays can be combined with plasmonic nanostructures in order to amplify the detected fluorescence signal [1]. Here, we present a substrate for plasmon enhanced fluorescence spectroscopy (SPFS) with epifluorescent readout geometry. The structure consists of a periodic array of gold nanoparticles supported by polymer pillars above a gold nanohole array, providing a rich spectrum of tightly confined modes. Fluorescence enhancement is achieved by the strong enhancement of local electromagnetic field intensity and density of states associated with these modes. Finite difference time domain (FDTD) simulations are employed to tune the resonant modes to optimize both, plasmonic amplification of excitation rate at the fluorophore absorption wavelength as well as providing directional emission at the emission wavelength. The emission of large portions of fluorescence light to a narrow solid angle simplifies the optical system required for rapid readout of fluorescence in array sensor format [2]. Substrates are prepared by nanoimprint lithography (NIL) with subsequent evaporation of gold, a method compatible with industrial scale roll-to-roll processes.

The presented system is developed for application in early stage detection of colon cancer, through the analysis of autoantibodies against tumor antigens circulating in blood.

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10231-78, Session PS

Overview of field gamma spectrometries based on Si-photomultiplier

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Completed analytical review of modern scientific, technical, regulatory and methodical literatures, affecting the scientific and technical problem of development of field gamma spectrometries based on Si-photomultiplier.

The basis of the national economy and industry are the country’s natural resources. Status and development of mineral complex, its technical and technological support to largely determine the economic, energy and military security of Russia and its geopolitical influence in the world. In modern conditions, there are special requirements to the technical and technological support of exploration work due to the exhaustion of the fund of subsurface, relatively easily discovered fields, as well as the fact that the search operation has to be carried out in severe geomorphological environments (large depth range, arctic latitudes and mountainous areas with no infrastructure, the shelf of the northern seas and etc).

This work is a part of project for mass production of a new generation of field gamma spectrometry equipment based on si-photomultiplier (SiPM), which has enhanced characteristics of sensitivity, accuracy and autonomy combined with low weight and size parameters.

An analytical review of modern scientific, technical, regulatory and methodical literatures are evaluated the current state of the global challenges and prepare the ground for the most effective organization of future research projects under this theme.

The main conclusions that can be drawn from the analysis include:

-for solid state SiPMs: Currently, a number of companies, including Philips, Sensl, Hamamatsu, KETEK, introduced to the market a number of commercially available SiPM, the functionality of which potentially satisfy the requirements of the project objectives. Thus the technical and cost characteristics of the receivers of different manufacturers are close to each other;

-for scintillation crystals and detectors on their basis: confirmed the preliminary information obtained under the scientific and technological potential of the traditional types of scintillators, recommended for use in detectors for field instrumentation. Among the commercially available scintillator can distinguish NaI (TI) and CsI (TI). For the first of them is characterized by high hygroscopicity, the second is a relatively low light output. Both of these factors must be considered when selecting the scintillator for gamma spectrometer field;

-the schemes docking scintillator and SiPMs: received information about how to use the most simple joining schemes in which the scintillator and sensitive area are connected by bonding to each other. This scheme does not involve any additional matching components. Its advantage is the relative ease of implementation, however, it can be assumed with high probability that such a scheme will not ensure obtaining specifications laid down in the specifications. This will require a complex work in terms of research and implementation of optimal mating scheme scintillator and SiPMs;

-in terms of the finished prototype of field gamma-ray spectrometers: information about the positive results of the development is received only about one product (gamma spectrometer MiniSpec, 2014). At the same time the technical parameters of the prototype are much smaller than the requirements laid down in the terms of reference for this project. For example, only the value of the measuring range MiniSpec 2 times inferiors to the design requirements. However, the experience gained by developers MiniSpec should be studied and used in the present draft.

10231-79, Session PS

An experimental sample of the field gamma-spectrometer based on solid state Si-photomultiplier

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The architecture of an experimental sample of the field of gamma-spectrometerwas developed. In the basis of the development approach was used a universal architecture and followed from it a single

Geophysical measurements can be considered as one of the most conservative types of measurements. Many years of experience in the research of geophysical fields were subdued in the first place, the requirements of high accuracy and adequacy of the measurement results (matching the real picture of the physical world). These requirements largely provide continuity measurement technology. As a result, the range of devices, their functionality, methodological and metrological support remained unchanged for decades.

It must be admitted that many users are quite satisfied with this state of affairs: the use of the same devices for tens of years ensures continuity of measurement technology, processing and interpretation of data.

A single instrument platform is a tool which allows you to use to provide a number of advantages such as consumer devices and systems, and their developers.

The consumer receives a group of field devices that solve different problems, but united by a number of common traits: a functional and ergonomic principles, a single field computer, unified command system, unified data exchange and formats of protocols, common methods of navigation, the use of wireless communication, operational communication with remote users.

In this case there is an additional possibility of combining multiple devices into a single measurement system. This allows, for example, to simultaneously measure various physical fields, such as radiation and magnetic fields. The costs of measurements are reduced almost twice. In this case the results of measurements of different physical fields are aligned in time and space, which gives new possibilities for the analysis of the nature of the anomalies, increasing the quality of data interpretation.

In turn, the developer is able to use the same carefully planned solutions for all devices of the group. For example, the software controller will be used regardless of the destination device, the development of specialized modules will be carried out within a single technology for integration with a single core. Add to this the unification of technology of preparation of documentation, implementation service, simultaneous transition of all of the family to the new version of the software.

The requirements for basic functionality of the field of gamma-spectrometer on the basis of solid-state silicon photomultiplier are laid down in the specifications on the prototype development, almost completely coincide with the requirements of modern geophysical measuring instruments. This allows you to extend the principles of the unified architecture, laid down in the development of the EA field gamma-ray spectrometer and other measuring geophysical instruments.

Among the specialized software and hardware components, the development of which is beyond the scope of standard solutions a single platform, and probably will not be transferred to other measuring geophysical instruments which are necessary to carry a measuring channel comprising a scintillator, solid state silicon photomultiplier and additional matching the optical and / or structural components, as well as specialized software application to be developed as part of the prototype gamma spectrometer:

-algorithm for automatic recognition of the spectra;

-algorithm for automatic detection of anomalies;

-mapping algorithm radiation areas.

10231-80, Session PS

Improved vibration sensor based on a biconical tapered singlemode fiber, using in-fiber Mach-Zehnder interferometer

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Optical fiber vibration sensors are the appropriate alternative for piezoelectric devices because they are not sensitive to electromagnetic external conditions. Most of the fiber optic vibration sensors demonstrated in previous publications resist on different interferometer or Bragg's gratings. Such sensors require a long time for stabilization of an optical signal, because they are vulnerable to undesirable disturbance. In majority, time response of an optical sensor should be instantaneous, therefore, we proposed in-line vibration sensing passive element based on tapered fiber.

Micrometer sized optical fiber tapers are attractive for many optical areas due to securing the operation based on changes of the boundary conditions for guided wave. Such phenomena allow for sensitive detection of the light with information written as phase modulation. Our experiment shows that a singlemode, adiabatic tapered fiber enables detecting acoustic vibration. In this study, we report on two configuration of a Mach-Zehnder (MZ) interferometer's vibration sensor composed on the basis of two 3dB couplers at 1550 nm. W used two set-ups with different configuration of reference arm consists 4 m of standard singlemode fiber. In sensing arm, as a vibration transducer we used the tapered optical fibers attached to the metal plate. Researches were carried out on different tapered configurations which the diameter of waist was in the range from 5 μm to 25 μm, and optical losses are always less than 0,5 dB.

Measured phase changes were in the frequency range from 100 Hz to 1 kHz and different acoustic power was generated by a speaker (amplitude from 100 mVpp to 1 Vpp). The discussion on the optimization of the taper structure for above conditions is included in the paper.

10231-81, Session PS

Development of an algorithm of the decision of the inverse ellipsometry problem for multilayer structure of the matrix receiver of optical radiation

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The complete and systematical research of the options affecting the quantity of the been taking electrical signal is important for the major of the modern matrix receivers, which are used video information devices. For the matrix receivers of optical radiation on basis of CCD and CMOS sensors, its work principle based on the image transformation into the digital signal, that option is sensitivity. During the analysis of the researching object it is necessary to take into consideration the fault brought in with the elements of electronic signal processing part. The instrumental fault influences, due to the irregular distribution of the sensitivity of the sensor platform, as a consequence of the irregular response of the sensor pixels of the matrix element. Therefore, during the faults' analysis of these devises, the dissimilarity of the optical characteristics and their elements must be taken in consideration.

To research this type of fault and its registration in the scheme of a particular device it is necessary to generate a mathematical model of the multilayer pixels' structure; its options can be determined by solving the inverse ellipsometry problem. The solution to the inverse ellipsometry is worked out and used in the analysis of a single layer system. The aim of the work is to adapt the solution of the inverse ellipsometry problem for a single-layer system of pixel, forming the structure of a color matrix of a video information receiver.

To get the initial data, which are necessary to solve the inverse problem, the ellipsometric measurements of the polarization angles for the radiation reflected from the air-surface interface of the sensor. These angles characterize a pixel structure of the matrix.

Solving the inverse problem of ellipsometry for such a system, it is possible to determine the thickness and refractive layers' indexes, forming the structure under study. That problem has no analytic solution in general form (except for the case of a clean surface without any covering). Thus, a large diversity of the numerical nonlinear methods are involved to solve it. Their basis – the multiple solution of the direct problem with the system options selected by some rules and comparing the calculated values of the polarization angle with the experimental one. The procedure continues till the difference between the calculated and experimental values of the polarization angles becomes less than some predetermined value. The inverse problem of ellipsometry for the multilayer system (in that case three layer), at each stage is solved within the limits of a single-layer model. The refractive indexes are determined with the reflection coefficient, expressing with the admittances Abele. Layer thickness is determined by the method of Holmes. The

measurements are carried out at two or more angles of incidence. That allows to specify the adequacy of the model and the real object on the convergence of the results at different angles of incidence.

In such a way , the algorithm for solving the inverse ellipsometry problem is done, so the thickness and the refractive index of the pixel's surface can be determined.

10231-82, Session PS

Photonic crystal fiber transducers filled with naonparticle mixtures for temperature sensing application

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Photonic crystal fibers (PCFs) with their inner air holes microstructure allow to modify and control propagation properties of the light propagated through them. Several applications focused on telecommunications, light sources and sensor technology were presented in which changes of air holes' lattices, sizes and their arrangements in the PCFs cross sections influence their dispersion characteristics. Another approach to introducing propagation properties' changes is to fill the air holes of PCF with a liquid material.

This fiber treatment allows us to design PCF transducers for a temperature threshold sensor. As a filling material we have selected a group of n-alkanes with melting points (MPs) within the range of 9 oC – 65oC and refractive indices between 1.431–1.450 (in their liquid states). A simple PCF transducer is a patch cord with a piece of a partially filled LMA-10 PCF spliced between two pieces of a standard telecommunication single mode fiber. Each of transducers has a bi-stable temperature characteristics. In a heating direction it is in OFF state when temperature is less than its MP but for higher temperatures it is in ON state. But when the transducer is cooled the ON/OFF states change at crystallization temperature which is different than MP. Thus, for all transducers between heating and cooling temperature characteristics we can observe hysterises. This effect is called as supercooling effect and in our work we will show how to reduce it by preparing mixtures of n-alkanes with gold nanoparticles to introduce heterogeneous nucleation centers.

10231-83, Session PS

Temperature and pressure fiber sensor based on air microcavity in PDMS

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Optical fibre sensors have unique properties such as small size, light weight, high sensitivity, biocompatibility, corrosion resistance, immunity to electromagnetic interference, continuous measurements and in-situ monitoring of chemical parameters in industrial processes. The sensors can work in different ways. One of the most sensitive ways is sensing measurands by the interference of light. Configuration of the interferometer depends on different parameters. Usually the interferometer consists of a set of mirrors dividing the light into arms, and then decoupled back to compare the phase of travelled light in particular arms. One interesting aspect of mirror creation is offered by a Fabry-Perot interferometer.

A preparation of polydimethylsiloxane (PDMS) Fabry-Perot interferometer located at the end of a single-mode optical fibre (SMF) is presented. A fibre tip is treated by applying thin paraffin wax film to the fibre end. Then the fibre end is packed with PDMS. After curing, the fibre end is heated to diffuse wax to the PDMS. This reduces the adhesion and allows the creation of the micro-cavity between the fibre end face and the PDMS layer. Then the length of micro-cavity is fixed by covering it with a second layer of PDMS.

Based on temperature and pressure influence we investigated the function of the fiber Fabry-Perot interferometer. When measurand is applied to such a Fabry-Perot interferometer, the length of the micro-cavity will change. So the wavelength shift of reference minima (maxima) of interference pattern corresponds to measurand change. For the operation of the sensor broadband light source and low-resolution optical spectral analyzer can be used. The sensor has small size and good mechanical strength.

10231-84, Session PS

Optical features of zinc selenide and silver iodide and two-phase composite nanostructures

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In recent years, formation of nanoscale structures by laser ablation becomes possible. Laser ablation is technique for creation thin films of nanostructures by substances evaporation from the target due to laser radiation heating and further deposition on a substrate. The control of growth semiconductor nanostructures parameters are required. The goal of this work is the investigation of optical spectra features of zinc selenide (ZnSe) and silver iodide (AgI) nanostructures produced by laser ablation method, which can be used to design optical sensors and diffractive structures in integrated optics. The discovered transmission spectra minima are shifted to blue wavelengths relatively to the bulk semiconductor material band edge, which corresponds to the effective band gap width increasing for the samples. The observed minima of the transmission spectra are peculiar to the quantum energy spectra of semiconductor nanostructures. The band gap broadening of the samples can point to the presence of nanocrystals in samples produced by laser ablation, which are characterized by the energy spectrum quantization and lower electron and upper hole quantum confinement levels shifts from the bottom of the conduction and valence bands, respectively. Quantum confinement additives to the band gap energies were estimated according to the transmission spectra. ZnSe samples transmission spectra showed a significant inhomogeneous minima broadening (≈0,3 eV), that can be explained by the sizes dispersion of the formed nanostructures. Furthermore, the transmission minima shifts to blue wavelengths for different samples are distinguished, that it is possible to explain by the different average size of the formed zinc selenide nanostructures. The transmission decrease with increasing wavelength with access to a minimum at the long-wavelength spectral region (550-900nm) and a further increase was observed. Decrease of the transmission in the long-wavelength region can be the evidence of the formed during the growth of semiconductor samples by laser ablation impurities or defects absorption levels. Transmission spectra of silver iodide samples performed the similar features as zinc selenide samples: presence of the transmission minimum at the short-wavelength spectral region, the transmission spectra minima shift to blue wavelengths region relatively to the bulk semiconductor AgI band edge. We have identified lower size dispersion of the AgI nanocrystals relatively to the ZnSe samples. Quantum confinement additives to the band gap energies (?E = hv-Eg_bulk) were estimated: 120-170 meV for ZnSe and 80-90 meV for AgI.

10231-85, Session PS

Gallium nanoparticles colloids synthesis for UV bio-optical sensors

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New methods for the production of colloidal Ga nanoparticles (GaNPs) have been introduced based on the evaporation of gallium on sacrificial aluminium zinc oxide (AZO) layer. The nanoparticles can be prepared in aqueous or organic solvents such as tetrahydrofuran (THF) or ethanol in order to be used in different sensing field. The particles had a quasi mono-modal distribution ranging from 10nm to 80nm as diameter and their aggregation status depended on the solvent nature. Compare to common chemical synthesis, our method may assures higher yield with the possibility of the particles size control by adjusting the deposition time. Moreover, a further functionalization of the nanoparticles before putting them in a solution is possible (thermal treatment, ion implantation). The GaNPs have been studied by spectrophotometer analysis to characterize the equivalent absorption spectra. The colloid solutions exhibit strong plasmonic absorption in the UV region around the 280 nm wavelength, which mainly depends to the nanoparticles dimensions and their aggregation state as the simulations confirmed. With regards of the colloidal GaNPs flocculate behaviour, the water solvent case has been investigated for different pH values. Jointly with use of the centrifugation process, it has been possible to estimate the relative absorption of different particles average size. Finally, it is possible to functionalize the solution by thiols through the formation of S-Ga bonds.1 This result opens the possibility of developing high sensitivity systems for molecular imaging in combination with DNA and biological sensor in a broad range of applications.2,3

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10231-86, Session PS

Luminance Compensation for AMOLED displays using integrated MIS sensors

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Active matrix organic light emitting diodes (AMOLEDs) are ideal for future TV applications due to their ability to faithfully reproduce real images. However, the use of poly-Si TFTs for large-area applications is challenging because of uniformity and scalability issues. It would be economically attractive to use existing production lines for fabrication of a-Si TFTs AMOLED backplanes. The main problem in this technology is that a Si:H pixel circuitry suffers from temporal instability caused by the threshold voltage shift of the driving TFT under prolonged bias stress and also degradation related to the OLED material itself. A tight control of pixel luminance can be achieved by measuring the emission from the OLED in real time and adopting a feedback control scheme. Here, we report on a pixel driver utilizing a metal-insulator-semiconductor (MIS) sensor for luminance control of the OLED element. In the proposed pixel architecture for bottom-emission AMOLEDs, the embedded MIS sensor shares the same layer stack with back-channel etched a Si:H TFTs to maintain the fabrication simplicity. The pixel design for a large-area HD display is presented. The external electronics performs image processing to modify incoming video using correction parameters for the each pixel in the backplane, and also sensor data processing to update the correction parameters. The luminance adjusting algorithm is based on realistic models for pixel circuit elements to predict the relation between the programming voltage and OLED luminance. Performance characteristics of the MIS sensor are presented and analyzed to demonstrate its feasibility. Details on the pixel circuit functionality including the sensing and programming operations are also discussed.

10231-87, Session PS

New fiber laser design for application in phase sensitive optical time domain reflectometry

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Linewidth narrowing of DFB lasers operating at single frequency is of great research interest due to its potential applications in distributed fiber sensing. The spectral performance of available DFB laser sources is significantly improved with implementation of self-injection locking mechanism. To provide the effect, a part of the optical radiation emitted by the laser should be returned back into the laser cavity. This relatively simple method is important to design cost-effective laser sources demanded, in particular, in phase sensitive optical time domain reflectometry.

In this work, we study self-injection locking of DFB laser obtained with a feedback loop that comprises a ring optical fiber cavity and apply the developed source for operation with the distributed acoustic sensor. In laser configuration a low-loss optical fiber ring resonator built from standard telecom components is used as a narrowband filter. The optical transfer characteristics of the ring resonator strongly depend on the coupling factor. Three different regimes of the cavity coupling have been considered: under-coupling, over-coupling and critical coupling. Although the laser locking has been achieved in all coupling regimes, we have demonstrated that only the critical coupling is able to provide the superior laser line narrowing in combination with operation stability. In this case, the laser power accumulated inside the cavity provides strong feedback for laser locking and leads to a significant narrowing of the laser emitted spectrum down to ~2.4 kHz.

In order to demonstrate potential of the proposed laser source we have applied it for detection of localized perturbations with the distributed acoustic sensor based on phase-OTDR. With the spatial resolution of 2 - 3 m we have demonstrated an accurate localization of 50 Hz harmonic perturbation of the fiber at the distance of 9270 m. The measured signal-to-noise ratio achieved with the proposed source is nearly the same as achieved with an expensive ~300-Hz-linewidth laser (OEwaves Inc.).

10231-88, Session PS

Simultaneous transmission of standard data, precise time, stable frequency and sensing signals and their possible interaction

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Fibre networks are the only way how to satisfy the ever growing needs for more bandwidth on long distances. Commercial optical transmission systems can transmit data at speed 400 Gb/s per one lambda and the total number of lambdas is up to one hundred or even more. But there are also other areas of fibre-optic networks, which are not focused only on enormous number of bits transmitted. New applications like accurate time transfer, ultra-stable frequency transfer have been rather common. Other area which has been developing rapidly in past years is fibre-optic sensing. Fibre-optic sensors are used in many areas of industry and it is clear that interest in these sensors increases every year. The most common sensors are based on back-scatterings and technique of optical time domain reflectometry is mostly used. High speed data transmission, time and frequency transmission and fibre-optic sensors must share the common fibre-optic infrastructure because it would not be economically feasible to build separate fibre networks. Unfortunately, accurate time signals are slow and often OOK modulated, therefore may experience the degrading effects of chromatic dispersion. Ultra-stable frequency signals are not modulated at all – information transmitted is the frequency of photons and such signals are continuous wave, but they suffer from phase noise also environmentally introduced, e.g. by vibrations. Whereas for OTDR sensor systems the high power pulses are necessary interference between individual applications can occur. For this reason, parallel and simultaneous transmission of standard data and time, frequency and sensing signals is rather new and unexplored area of research.

10231-89, Session PS

Continuous palladium-based thin films for hydrogen detection

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Palladium-based continuous films have been largely employed as chemoresistor and Surface Plasmon Resonance (SPR) sensors, but the focus has not been set on the development of simple absorbance based sensors so far.

Thin films of Pd have been deposited by evaporation technique and have been later treated to achieve metal-oxide films. The Pd-oxidized samples display strong variation in structural and optical properties, when exposed to reducing gases and have been tested toward oxidizing/reducing gases.

In addition, Pd-Sn films have been produced. The development low cost sensors is of crucial importance. In this direction, the alloying of palladium with a cheaper material, as tin, may lead to a sensitive cut of costs, together with high yield techniques of deposition, such as evaporation that allows the covering of wide substrates.

The structure and morphology of the Pd-based films have been investigated and the changes have been related to the optical properties using spectroscopic ellipsometry and UV/Vis/NIR absorption spectroscopy, allowing a deep understanding of the optical gas sensing behavior of Pd, Pd-oxidized and Pd-Sn thin film.

The sensing performance in absorbance-mode of the films have been also compared to their sensing behavior in SPR configuration. In this case the metallic surface has been functionalized with a thin layer of graphene.

10231-90, Session PS

Tiny incident light angle sensor

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A novel optical detector for measuring the solid angles and intensity of incoming light is presented. By analysis of only four signals it allows for measuring the angles in a range of 0° to 85° and 0° to 360° with an accuracy of 0.2° for the elevation and 5° for the azimuth, respectively. Target applications are smart displays, active air conditioning controls (automotive), alignment control of solar energy systems and general lighting applications.

The monolithic silicon sensor with 1 x 1 mm? base area uses the same strategy as classical plane four quadrant photodiode: the ratios of the four signals are used for calculating the illuminating spot position. In contrast, the sensitive areas in the presented device are integrated in the inclined side walls of an inverse pyramid, which has been anisotropically deep etched into the silicon wafer. Due to the resulting angular dependency of the projected active areas the direction of the incoming light can be evaluated.

We will present the principle manufacturing steps leading to these results as well as a model used for prediction of sensor functionality. This model is based on two steps: (A) an optical part realized in ZEMAX and (B) a geometry and angle depending semiconductor simulation. While (A) is used for calculating the distribution of light intensity and incident angles, (B) simulates the resulting sensor signals and characteristic curves. The combined model was used for design optimization. The optimized design possesses a high angular resolution and a larger angle measurement range in the half-space. It features four channels; each of them has a flat as well as an inclined sensitive area. We will demonstrate calibration measurement setup and obtained characteristic curves. A neural network was used in order to calculate the incident light direction, i.e. both solid angles, from the four sensor signals.

10231-91, Session PS

Miniature optical components for a small inline polarimeter

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We present two novel components for a small polarimeter: A laser light source and a polarization measuring element. The polarimeter is designed for the use in experimental biogas fermenters, where the optical activity information is needed as an input for the process control loop. For this purpose reproducible measurements over several days and a very small sample volume are necessary. The polarimeter features an error detection capability for beam alignment, no moving parts, and a sample volume of less than 0.7 ml for 10 cm path length. The accuracy lies in the range of 1/100°, which is adequate for the determination of the saccharine content inside the fermenter.

The laser light source provides the collimated and linearly polarized light which passes the sample chamber towards the polarization detector. The beam diameter is smaller than 1 mm (typically 500 μm) over the whole length of 10 cm in order to prevent reflections from the chamber walls. The micro lasers are surface emitting laser diodes (VCSELs) that are mounted on a metalized glass / polymer micro optics in a wafer based process flow. This makes it possible to reduce the size of the polarized light source down to 1.40 x 0.64 x 0.70 mm?.

The polarization angle detector consists of a beam polarizing splitter cube with a splitting ratio of better than 10000:1. At both exits a monolithic pair of photodiodes is mounted directly. The sum of the two signals is a measure for the parallel or perpendicular polarized part of the light, respectively. The double diodes are tilted by 90° within the plane, in order to create a four-quadrant detector that is suited to analyze the beam position. This additional position measurement is used for detection of adverse illumination.

10231-92, Session PS

Interaction of Amyloid-? peptides with lipid bilayer investigated by supercritical angle fluorescence

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Processes occurring at the interface between two media are of prior importance in various fields of research, from material sciences to biology.

Therefore, the understanding of these interfacial events has gained an increasing interest over years. Low-invasive optical spectroscopy methods are highly suitable for these researches. However, an important challenge is to isolate the weak interfacial signal from the bulk sample signal. Our group developed a custom-made microscope objective which allows this separation through two distinct collection volumes. This objective simultaneously collects light beyond and below the critical angle of total internal reflection of a water/glass interface. The so-called supercritical collection gives a near-field detection volume while the undercritical one provides a classical confocal detection channel. So, the objective carries out a surface-sensitive spectroscopy and isolates this signal from the bulk solution radiation, while still collecting it. That feature is particularly interesting to probe aqueous samples related to biological interfacial events. A biological example of particular interest is the comprehension of neurodegenerative diseases which seem caused by the interaction of specific peptides with the membrane of the neurons. Taking advantage of our optical setup, we used fluorescence spectroscopy to specifically monitor the interaction between a supported lipid bilayer and the Amyloid-? peptide, notably responsible of the Alzheimer disease. This depth-selective analysis mimicked and covered the adverse effects of the peptide interaction with the neuron membrane, as much as the kinetic and affinity of its adsorption on the lipid bilayer. Various lipid composition as much as different forms of the peptide (40 and 42 amino acids composition) were tested. The results emphasized some hypothesis which attribute the toxicity of the peptide to a partial disruption of the lipid membrane, the effect being even more pronounced with the aggregated oligomeric form of the amyloid-?.

10231-93, Session PS

Advanced wide-field surface plasmon microscopy of single adsorbing nanoparticles

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Detection and characterisation of nanoparticles (NPs), especially in complex biological media, still represent a major challenge for existing analytical methods. In the present work we describe a label-free, real time and cost-effective analytical method for detection of NPs with very low concentrations in real samples of consumer products. In second part, we also address the problem of electrochemical characterisation of single NPs.

Proposed methods are based on the wide-field surface plasmon microscopy (SPM). The large field of view of our SPM setup (~1.3mm^2) allows the detection of single adsorbing nanoparticles up to the hundreds of thousands. The minimal detectable size of NP is ~15-20 nm for the Au NPs, ~40-50 nm for polystyrene NPs. The detection rate is proportional to a volume concentration of NPs over several orders of magnitude concentration range: typically 10^6-10^10 NPs/ml. This range can be further improved tenfold.

For the detection of NPs in complex media the influence of matrix effects should be considered. To effectively discriminate images of NPs from image perturbations caused by the matrix components, we propose to use the template matching. First, the characteristic SPM images of nanoparticles (templates) are collected in aqueous suspensions. Then the detection of nanoparticles in complex environment using template matching is performed. Using this approach, the detection and characterisation of various NPs in consumer products like sunscreen cream, mineral water, juices, and wines was shown at sub-ppb level (~100 pg/mL).

Characterisation of detected NPs can be done by their images, but, unfortunately, the size/material can not be resolved directly. For determination of chemical composition of single NPs separately, SPM can be assisted by electrochemical analysis. In this case, the gold sensor surface is used both for plasmon microscopy and as a working electrode. Applying the linear sweep of potential to this electrode, adsorbed NPs can be subjected to electrochemical dissolution, whose potential characterises its material.

10231-94, Session PS

Development of optical planar waveguide biosensor for detection of mycotoxins

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I. INTRODUCTION

The detection of toxins is one of the main tasks nowadays for environmental science, security, agriculture, food industry, and medicine. A particular interest was on detection of mycotoxins, the products of metabolism of numerous fungi species, which appeared to have toxic, carcinogenic and hormone disruptive effects on humans [1]. The WHO legislated a limit for mycotoxins in food and feed in ppb concentration level which makes the detection of small mycotoxin molecules (typical molecular weight in hundreds Dalton) a formidable task. The existing high-tech analytical methods such as HPLC or mass-spectroscopy can provide the required sensitivity but they are expensive and time consuming, therefore the development of bio-sensors for toxin detection is in great demand nowadays. Highly sensitive optical immuno-sensors are leading in this development [2]. Our previous research exploiting the method of Total Internal Reflection Ellipsometry (TIRE) combined with direct immunoassay format showed high sensitivity (in sub-ppb range) of detection of different mycotoxins [3-5]. The use of a planar waveguide operating as polarization interferometer [6] is a logical continuation of this work towards the development of portable sensor devices. Preliminary experiments and modelling showed potential increase in sensitivity in 2 to 3 orders of magnitude because of multiple reflections of light in the waveguide [5]. Several successful biosensing developments based on planar waveguides [7, 8] including fully integrated biosensor [9] appeared recently and demonstrated remarkable sensitivity. The main aim of this work was to explore the advantages of planar waveguides and to develop a highly sensitive immuno-sensor capable of detecting small toxin molecules, particularly mycotoxins, in very low concentrations in ppt range.

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II. SENSOR DESIGN

The planar waveguide structure was produced on silicon wafers using standard microelectronic processes and consisted of a thin (200nm) layer of Si3N4 sandwiched between much thicker (3?m) layers of SiO2. Because of a large difference in refractive indices of Si3N4 core (n=2) and SiO2 cladding (n=1.46), the light propagates at an angle of 47o and thus experiences about 3000 reflections per mm (Fig. 1a). In the experimental polarization interferometer set-up in Fig. 1b, 630nm light from a fan-beam laser diode was coupled through the slant edge of the waveguide and collected on the other side with a CCD array. A polarizer in front of CCD camera allows the detection of a phase shift between p- and s- components of polarized light. The reaction cell equipped with inlet and outlet tubes is sealed against a sensing window which was etched in the top SiO2 layer and then coated with a bio-sensing layer. Any changes in refractive index or thickness of this sensing layer affect mostly p- component of polarized light, while s- component acts as a reference, thus resulting in a multi-periodic output signal (Fig. 1c) Vout =A. Cos (??), where ??????p?????s is the phase shift between p- and s- components.

The photographs in Fig. 2 show the general view of PW bio-sensor set-up (a) as well as the light coupling (b) through the waveguide slant edge (top) and the out-coming light (bottom).

Currently, the analog signal averaging light intensity in the active area of Thorlab LC100 CCD camera, is recorded using PicoScope connected to PC. The work is currently underway to perform data acquisition and further processing using National Instrument card and LabView dedicated software.

III. TESTING THE EXPRIMENTAL SET-UP.

Prior to testing the PW set-up, the sensing window in the top SiO2 layer of the waveguide was in diluted 1:10 HF into the cell. Testing the waveguide sensor was carried out by injecting the NaCl solutions of different concentrations into the cell. Typical multi-periodic output signal is shown in Fig. 3.

The number of periods of signal oscillation can be roughly estimated from these waveforms. The results of such tests summarized in Table 1 allows estimating the refractive index sensitivity (RIS) of PW sensors.

The obtained RIS values are also shown in Table 1. Similar to the Mach-Zehnder interferometer [8] the phase shift ???depends on the refractive index variations for p- and s-components of polarized light: ??? = 2?(L/?)(?np-?ns), so that the phase change can be calibrated by changes in the refractive index of a medium.

TABLE 1. Evaluation of refractive index sensitivity (RIS)

NaCl%	n	?n	No of periods	RIS (rad/RIU)
3	1.3383	0.0053	~1	1186
5	1.3418	0.0088	~2	1428
10	1.3505	0.0175	~3.5	1257
15	1.3594	0.0264	~4.5	1070
20	1.3684	0.0354	~6	1064

Average RIS = 1201±114 rad/RIU

An average refractive index sensitivity of around 1200 radians per refractive index unity was calculated which is quite remarkable since it is much higher than in other traditional optical methods such as TIRE or SPR though nearly 3 times smaller than that reported for MZ interferometer devices [2]. Incomplete etching of top SiO2 layer might be responsible for that, so the use of photolithography in commercially fabricated planar waveguide devices is expected to improve RIS.

More detailed and accurate analysis can be performed using Fourier Transform of the experimental waveforms. MatLab spectrogram tool was utilized for this purpose, and the resulted pseudo-3D diagram of the signal in Fig. 3 is shown in Fig. 4 as an example. The decrease in the main oscillation frequency with time is apparent. The values of frequencies can be further converted into periods, and eventually resulted in the time dependence of a phase shift. In future, such data analysis will be carried out in-situ using LabView software.

IV. BIOSENSING EXPERIMENTS.

A series of tests of sequential deposition of layers of polyelectrolytes PAH (poly-allylamine hydrochloride) and PSS (poly-sterylsulfonate sodium salt) have resulted in progressive increase in the phase shift. Further experiments of detecting Aflatoxin B1 (one of the common mycotoxins) in direct immunoassay with specific antibodies was carried out. For this purpose, according to the procedure of electrostatic immobilization of proteins developed earlier [3-5], the following adsorption steps were performed: (i) deposition of positively charged polycationic PAH layer; (ii) deposition of Protein A (negatively charged at pH 7), (iii) deposition of monoclonal antibodies to aflatoxin B1 (binding to protein A at the second domain), and finally (iv) binding of aflatoxin B. The PW sensor waveforms were recorded during the above these adsorption or binding stages and presented in Fig. 5.

As one can see, the number of periods on the waveforms corresponds well to the optical density of molecular layers deposited. There is a noticeable signal of about half a period of phase change was recorded upon binding 1ppb of aflatoxin B1, which is quite remarkable.

V. CONCLUSIONS AND FUTURE WORK.

The experimental set-up of planar polarization interferometer was developed and tested. The refractive index sensitivity of 1200 rad/RIU was evaluated. Preliminary biosensing experiments of detecting aflatoxin B1 in direct immunoassay with specific antibodies were successful; bio-sensor was capable of detection of 1 ng/ml of aftatoxin B1. The work is currently underway. Further development focuses on improvement of optical design (the use ? wavelength plate), the data acquisition using NI card and LabView software, and the use of photolithography in the fabrication of planar waveguide devices. Significant improvement in the sensor performance and its sensitivity is expected in near future.

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10231-95, Session PS

Preparation of Mach-Zehnder interferometric photonic biosensors by inkjet printing technology

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Inkjet printing is a versatile method to apply surface modification procedures in a spatially controlled, cost-effective and mass-fabrication compatible manner. Utilizing this technology, we investigate two different approaches for functionalizing label-free optical waveguide based biosensors: a) surface modification with amine-based functional polymers (biotin-modified polyethylenimine (PEI-B) [1]) employing active ester chemistry and b) modification with dextran based hydrogel thin films employing photoactive benzophenone crosslinker moieties [2]. Whereas the modification with PEI-B ensures high receptor density at the surface, the hydrogel films can serve both as a voluminous matrix for receptor molecules and as a semipermeable separation layer between the sensor surface and the sample. Applying multi-step printing procedures, the two approaches can easily be combined. We use the two surface modification strategies both individually and in combination for binding studies towards the detection of the protein inflammation biomarker, C-reactive protein (CRP). The aim is to develop a surface modification optimized for detection of CRP in whole serum samples in the clinically relevant concentration range. As the transducer, we use an integrated four-channel silicon nitride (Si3N4) waveguide based Mach-Zehnder interferometric (MZI) photonic sensing platform operating at a wavelength of 850nm (TM-mode) [3].

Printed hydrogel films were pre-characterized towards their thickness and swelling behaviour using atomic force microscopy conducted in air and liquid. The swelling ratio was found to be dependent on the irradiation dose used for crosslinking. A printing procedure was developed to ensure coverage of waveguides with a hydrogel layer of at least 500nm thickness in the swollen state. MZI-sensors were modified with PEI-B and hydrogel films were printed on top to investigate their separation layer properties. With streptavidin binding experiments we could show that the permeability of the hydrogel films for differently sized proteins, such as streptavidin, biotinylated bovine serum albumin, biotinylated antibodies

(anti C-reactive protein) and C-reactive protein decreases with increasing crosslink-dose. Hydrogel films, comprising PEI-B only within the hydrogel network, were obtained with inks containing both dextran and PEI-B. Streptavidin binding signals proved the permanent incorporation of the PEI-B as well as the ability of the hydrogel to support streptavidin/biotin binding.

Sensors modified both with PEI-B at the surface and with PEI-B containing hydrogel showed an increased sensor response upon streptavidin binding compared to sensors modified with PEI-B on the surface only. First CRP-binding results employing biotinylated antibodies, specific for CRP, were promising.

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10231-96, Session PS

Plasmonic absorber for selective photofunctionalization

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Plasmonic biosensors based on metallic nanostructures are able to monitor the surface biomolecular interactions in real-time [1]. Their response is high when analytes bind to the areas where plasmonic hot-spots are excited, such as to the edges or apexes of nanodisks or nanorods. In order to maximize biosensor response, methods for selective functionalization of these areas are highly desirable. Photoinduced surface reactions offer a simple strategy for spatially localized surface functionalization [2]. However, the photoactivable reagents are sensitive to ultraviolet (UV) light, whereas surface plasmons on nanostructures based on silver or gold can be excited by visible or infrared light. Moreover, UV light can be damaging for typical biomolecules.

In this study, we propose a plasmonic nanostructure which employs two sharp resonances to overcome these limitations and to achieve combined functionality: i. photofunctionalization in UV, ii. optical sensing in the visible spectral range. The plasmonic nanostructure consists of a sparse array of aluminium/gold nanopillars standing on dielectric/aluminium bilayer. The sparse array of bimetallic nanopillars allows for excitation of plasmon resonances with high-field enhancement, while the bilayer works as a reflective mirror to create Fabry-Pérot resonator. The combination of these two effects ensures almost complete absorption of light and high-field enhancement in the relevant spectral and spatial regions. The nanostructure is optimized by finite-difference time-domain (FDTD) method (Lumerical) and fabricated by electron beam lithography. The nanostructure is characterized using the scanning electron microscopy and the optical properties are verified by UV/visible spectroscopy.

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10231-97, Session PS

Optical sensors based on photonic crystals: a new route

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The realization of miniaturized devices able to accumulate a higher number of information in a smallest volume is a real challenge of the technological development. This trend increases the request of high sensitivity and selectivity sensors which can be integrated in microsystems. In this landscape, optical sensors based on photonic crystal technology can be an appealing solution [1, 2, 3] in order to have high performances sensors with miniaturized sizes. Traditionally, photonic crystal structures can support resonances strongly confined into a cavity or due to the coupling of guided modes in photonic crystal slabs [4, 5]. In the last years the perfect confinement of radiation in a photonic crystal thin slab together with a very high Q-factors resonances, has been explored [6, 7, 8]. These electromagnetic modes, named Bound States in Continuum (BIC), are characterized by theoretically zero bandwidth and can be excited by the external radiation.

In the following a new refractive index sensor device, based on the BIC resonance shift, is presented. A microfluidic cell allows the controlled injection of fluids with different refractive index on a Silicon Nitride photonic crystal slab supporting Bound States. The shift of very high Q-factor resonances excited into the photonic crystal open cavity is monitored. Good sensitivity and optimal stability are found.

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10231-98, Session PS

Real-time temperature monitoring during radiofrequency treatments on ex-vivo animal model by Fiber Bragg Grating sensors

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In the last decade, optical fiber technology has proven to be a viable option in several bio-medical applications. Indeed, due to their high precision, high resolution, small dimension, flexibility and high temperature endurance, fiber optics' utility to the biomedical field is undoubtedly a valid alternative to traditional sensing techniques.

Out of all fiber optic technologies, Fiber Bragg Gratings (FBGs) are, in particular, lightweight, small, minimally invasive, biocompatible, non-toxic and chemically inert. They therefore can be easily embodied into surgical instruments such as catheters and needles and their use produces no adverse biological effects to the human defense system, minimizing contamination and infection. FBG sensors allow the possibility to selectively detect and measure physiological parameters such as strain, temperature, pressure, and vibration, with the ultimate aim of improving medical surgery and rehabilitation.

Herein we propose the use of FBG sensor arrays for accurate temperature measurement during a multi-step RadioFrequency Ablation (RFA). RFA is considered one of the most minimally invasive techniques for the cure of small tumors as it exposes cancerous cells to a rapid temperature increase by way of RF discharge resulting in immediate cancerous tissue necrosis while allowing for the preservation of as much healthy tissue as possible. As such, highly accurate measuring of tissue temperature in the RF-applied region of an organ may be beneficial for determining the outcome and success of the thermo-ablation procedure. Until now, several external methods have been explored for temperature measurement during RFA treatments such as thermocouples, image-based thermometry and ultrasound imaging. In comparison with these other technologies, FBGs are insensitive to electromagnetic fields, electrical immune and safe, and compatible with computed tomography (CT) and magnetic resonance (MR) guided procedures, which are the standard image-guiding procedures that accompany RFA treatments.

In order to create a thermal multi-point map around the perimeter of the surgical area to be treated, through experimentations we developed a proper sensing configuration, which is presented herein. We outfitted the RF probe of a commercial medical device equipping it with several packaged FBGs sensors. Moreover, in order to measure the treated area as accurately as possible, a second linear array of 3.5 cm in length was created using several FBGs.

This work presents the results of our RFA experiments carried out on ex-vivo animal liver and kidney tissues. Thanks to the array sensors, we were able to identify and measure the temperature change with a fast response time and high spatial resolution. The proposed FBGs-based solution is able to distinguish different and consecutive discharges and as well as measure the temperature profile with a resolution of 0.1 °C and a minimum spatial resolution of 5 mm for each discharge. Based upon our experiments it is possible to confirm that the temperature decreases with distance from a RF peak ablation, in accordance with RF theory.

The proposed solution promises to be very useful for the surgeon because a real-time temperature feedback allows for the adaptation of RFA parameters during thermal ablation surgery and better delineates the tumor area under treatment.

10231-99, Session PS

Digital imaging spectroscopy technique for biological sensing

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A new two-dimensional digital imaging spectroscopy measurement system for detecting all anisotropic parameters of turbid media is proposed. The validity of the proposed technique is confirmed by the experimental results of extracting optical properties of chicken breast samples. The experimental result of extracted parameters was then compared with those obtained from simulation results. The results show that linear birefringence property is independent to the scattering effects. Furthermore, the linear birefringence property decreases with the increase of circular birefringence property in chicken breast sample. In general, the proposed technique provides a potential and flexible method for biological sensing applications.

10231-100, Session PS

Development of an optical biosensor for the detection of antibiotics in the environment

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Pharmacologically active substances like antibiotics, hormones, x-ray contrast media, antirheumatic drugs or beta blockers are increasingly accumulating in the environment. On the one hand pharmacologically active substances can be found in surface waters and on the other hand they food can be contain. In surface waters, they get there especially by incorrect disposal or by human and animal feaces. The reason is, that drugs are removed only incompletely during the wastewater treatment. In the case of food all animal products like milk, cheese, eggs or meat could be concerned. The use of animal drugs in the animal production is allowed and usual. But after the application of such drugs it is possible that residues or their decomposition products still stay in the animal carcasses.

To protect humans, animals and the environment, it is unavoidable to develop suitable detection technique and methods of quantification. Normally, common analytical methods are instrumental analysis, although biosensors particularly optical biosensors have a lot of advantages like lower sample volumes, faster analysis times and the possibility to perform on-site measurements.

In this work we will present the first steps of the development of an optical Biosensor for the antibiotic penicillin G. This biosensor is based on a label-free and time resolved method named Reflectometric Interference Spectroscopy (RIfS) [1, 2]. The method uses interference of white light at thin layers to observe molecular interactions.

The required surface modifications for the sensor were developed and optimized. Moreover, concentration dependency measurements in buffer were performed. The next steps will be the performance of a calibration curve and the observation of good recovery rates. Furthermore, we will transfer the Immunoassay to environmental matrices like milk and surface waters.

10231-101, Session PS

Revisiting the biosensing potential of a plasmonic metamaterial supporting a guided mode

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With rapid developments in the field of nanoplasmonics, a broad variety of novel plasmonic phenomena on various nanostructures have been introduced as alternative approaches to surface plasmon resonance (SPR) biosensing. Recently, a plasmonic metamaterial comprised of dense packed plasmonic nanorods supporting a guided mode has been proposed for sensing purposes, showing extremely high sensitivity to bulk refractive index. In this work, we revisit the sensing potential of this type of sensing structure through investigation via approaches relevant for biosensing applications. We examine the optical response to refractive index changes confined within a small volume at the proximity of the active sensing surface and, furthermore, investigate correlations with both bulk sensitivity and the distribution of the electromagnetic field. We will discuss the geometrical parameters of the plasmonic structures investigated as well as the critical role of the substrate. Apart from the optical properties, we also consider aspects related to the mass-transport of the analyte to the binding sites on the active sensing area, studied in terms of kinetic parameters of the assay.

The optical performance was calculated by a recently developed (approximate) analytical model based on effective medium

approximation and transfer-matrix method; results are compared with the rigorous coupled-wave analysis. The mass-transport performance is estimated using a recently developed analytical model, verified both by numerical simulation as well as experiment. The combination of these models provides a design guideline towards such sensors: we show that under proper conditions, the biosensing potential of a nanoparticle array can exceed that of a conventional SPR sensing structure (based on the continuous gold layer) by over an order of magnitude.

10231-102, Session PS

Fabrication of arc-induced long-period gratings in different silica fibers

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Long Period Gratings (LPGs) are periodic structures that couple co-propagating modes in optical fibers, resulting in several attenuation bands in the fiber transmission spectrum. Since the coupling changes with wavelength, the LPG acts as a wavelength-dependent loss element. LPGs are important in optical communication systems as well as in physical and chemical sensing application due to their sensitivity to strain and temperature induced effects and to surrounding refractive index.

LPGs are obtained by properly inducing a period perturbation in the refractive index and/or in the geometry of the optical fiber. LPGs typically have a grating period in the range of from 100 ??m to 1 mm. Various techniques have been proposed to fabricate LPGs ranging from main approach based on UV radiation to simpler procedures involving CO2 lasers, infrared femtosecond lasers, and electric arc discharge.

Among the different available techniques, the Electric Arc Discharge (EAD) has experienced wide diffusion during the last years since it is a simple, flexible and low cost procedure. EAD leads to a point-by-point LPG inscription, due to localized tapering of the transversal size of the core and cladding regions along the fiber, and to changes of the silica refractive index due to the stress relaxation induced by local hot spots. The main advantages of the EAD-based technique is that, in principle, it allows the fabrication of LPG in all kind of optical fibers. However, the application of the EAD procedure to different fibers demands hard work to select the right combination of the ARC power, ARC duration, fiber stretch and finally electrodes gap to fabricate good gratings.

In this work, we report on recent results about the fabrication of Long Period Gratings (LPGs) in different single mode optical fibers, by means of Electric Arc Discharge technique. We take into consideration silica fibers from standard SMF28 to unconventional ones and to hollow core fibers. The aim of the present work is to identify an appropriate "recipe" for each fiber for manufacturing LPG with strong and narrow attenuation bands and trivial power loss. Indeed, a proper combination of arc power and duration, as well as fiber tension, allows for the appropriate core and cladding modulation and thus for the desired LPGs spectral features. The sensitivity characteristics towards surrounding refractive index (SRI) and temperature changes of these LPGs are also investigated.

10231-103, Session PS

Effects of thermal and mechanical loads on the star sensor baffle

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Baffles are connected in front of the space cameras and star sensors to prevent the stray lights entering to the electro-optical system. Star sensors are mounted in various places of a spacecraft and imposed to different mechanical and thermal loads. In this research a star sensor baffle with a specified dimension is considered to simulate and analyze the deflections in various conditions. Vibration force from the launcher and gravity force considered as the mechanical load. Launcher vibrant force considered as QSL force and heat load is only considered from the solar radiation and have been modeled for both cold and hot cases. Deflection of the baffle is obtained using finite element method. Heat and mechanical loads are considered both at the launch time and in the orbit. Different materials such as aluminum, titanium, and CFRP composite are selected to do comparison among them. Composite materials are considered in many layer orientation configurations. Monte Carlo method is used to do ray tracing and obtain the efficiencies of the baffle to prevent the stray light entering to the entrance pupil diameter of the camera. Results show that baffles in launch time suffer from some deflections that affect the performance. In the orbit condition, baffles have negligible deformation although the thermal part is dominant. In launch condition, deflection mainly caused from the mechanical load. In orbit condition, deflection mainly caused from the heat load.

10231-104, Session PS

Surface functionalization for extreme localization of biological events and sub-protein tracking

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The use of labels to study biological processes has attracted a great deal of attention in the last years. In that respect, nanoparticles have arisen as a good option for this purpose due to their exceptional capabilities for creating strong contrasts from the background signal, via fluorescent or elastic scattering processes. The latter has demonstrated the advantage of overcoming the limitations of fluorescent labels, such as the saturation of fluorescent signal or photobleaching [1]. Among all the possible scatterers, gold nanoparticles (GNPs) have shown a great potential thanks to their ease of synthesis and well-known surface chemistry, especially relevant for the conjugation of the GNP with a certain biomolecule (e.g. proteins or DNA strands) [2]. These surface functionalization processes typically rely on the chemisorption of highly-specific molecules, to further anchor the target biomolecule selectively on the GNP surface through covalent bonds.

Recently, we have demonstrated that GNPs as small as 2 nm can be localized using interferometric detection of scattering (iSCAT) with only a few-nm precision opening a new avenue to track intra-molecular processes [3]. However, the new performance level of microscopy studies challenge the state-of-the-art in nanoparticle functionalization. In this paper we focus on optimizing the functionalization with respect to the distance between nanoparticle label and the respective binding site allowing us to closely track dynamical events at a few-nm length scales. We discuss the compromises, specificity and robustness of the tight functionalization schemes for application in biophysics and molecular biology.

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10231-105, Session PS

Onboard TDI stage estimation and calibration using SNR analysis

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Electro-Optical design of a push-broom space camera for a Low Earth Orbit (LEO) remote sensing satellite is performed based on the noise analysis of TDI sensors for very high GSDs and low light level missions. It is well demonstrated that the CCD TDI mode of operation provides

increased photosensitivity relative to a linear CCD array, without the sacrifice of spatial resolution. However, for satellite imaging, in order to utilize the advantages which the TDI mode of operation offers, attention should be given to the parameters which affect the image quality of TDI sensors such as jitters, vibrations, noises and etc. A predefined TDI stages may not properly satisfy image quality requirement of the satellite camera. Furthermore, in order to use the whole dynamic range of the sensor, imager must be capable to set the TDI stages in every shots based on the affecting parameters. This paper deals with the optimal estimation and setting the stages based on tradeoffs among MTF, noises and SNR. On-board SNR estimation is simulated using the atmosphere analysis based on the MODTRAN algorithm in PcModWin software. According to the noises models, we have proposed a formulation to estimate TDI stages in such a way to satisfy the system SNR requirement. On the other hand, MTF requirement must be satisfy in the same manner. A proper combination of both parameters will guaranty the full dynamic range usage along with the high SNR and image quality.

10231-106, Session PS

Strain-based multicore fiber optic temperature sensor

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In this paper, intrinsic properties of the four-core optical fiber are utilized to perform strain induced temperature measurements. A four-core optical fiber allows light to couple into the cores within a single cladding of 125 um in diameter and generates an interference pattern of the light beams at far end. One may assume that each fiber core corresponds to an arm of the Michelson or Mach-Zhender interferometer to form an interferogram.

When temperature is applied to the fiber, since all cores are affected identically, there will not be any path difference between the waveguides in four cores to cause any fringe shift. Hence, the phase change is not influenced by the thermo-optic effects. In contrary, bending the multi-core fiber leads to a shift in phase. The sensor geometry used in the experiment, which is based on the thermal expansion of the steel rod makes the bending property to construct a temperature sensor.

An optical fiber part with a length of 12.3 cm is wound around a solid stainless steel cylinder to obtain a tight circular loop. When temperature is increased from 50 ºC to 92 ºC by a heat plate, the diameter of the rod measured by a Vernier calipers is raised from 3.776 cm to 3.778 cm. The temperature induced radial expansion of the stainless steel cylinder with an amount of 0.02 mm introduces a shear strain in the fiber loop. Due to the geometry of the fiber ring, the outer core pairs are more stretched than the inner ones, which leads an optical path-length difference between the waveguiding cores. Thus, results in a phase shift in the interference pattern of the four-core fiber, which is monitored by a CMOS camera. A MATLAB code is used to analyze the interferogram frames during the phase change. When the phase shift occurs, the intensity distribution of the selected part of the fringe pattern varies. Since the observed phase shift is two dimensional, after horizontal and vertical phase shifts are calculated, the total phase change is determined using the Pythagorean Theorem. A linear relationship between temperature and the phase of the guiding laser light is observed. The method also allows determining the value of the shear strain with a good precision. The sensitivity of the four-core fiber is determined to be 3.74 rad/m?C.

10231-107, Session PS

Heat transfer measurements with a four-core optical fiber

Sema Güvenç, Mehmet Naci Inci, Bogazici Univ (Turkey)

Fiber optic interferometry is one of the most promising branches in the field of optical sensing. To detect the temperature changes and the heat transfer rates, many successful experiments have been carried out before. In almost all of these interferometric sensor applications, the intrinsic properties of single-mode and single-core optical fibers are used as the sensing mechanism.

In this work, unlike the other experiments, a four-core optical fiber is introduced as a calorimetric gauge for heat transfer measurements. The aim of the study is to obtain heat transfer data through the temperature induced shift in the interference pattern of the four-core optical fiber at the far field upon applied heat pulses onto the distal end face of the fiber core. Heat pulses from a Nd:YAG laser are sent onto one of the four fiber cores axially. The fiber core serves as a calorimetric gauge with an infinite length compared with the diffusion length and preserves the accumulated heat supplied by a discrete laser pulse, which introduces a variation in the refractive index and the fiber length, resulting in an optical path difference between the four-guiding fiber cores. The optical path difference between the four fiber cores is monitored through the shift in the fringe pattern by a fast camera. The amount of the accumulated heat, temperature change, and the total phase shift in the sensitive part of the four-core fiber is determined using Fourier Heat Equation. One of the unique features of this mechanism is that the length of the four-core fiber is thought as infinite when compared to the heat diffusion length, which enables no heat loss along the fiber core and decreases error rates in the measurements.

10231-108, Session PS

Correlation of optical crosstalk performance of proximity-sensing device to the module's absolute package height

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Achieving optical sensing applications with minimal crosstalk is a great challenge as the trend to go to smaller packages, lower cost and more challenging applications arise. One of the growing trend in the optical sensing industry today is to have proximity sensing apparatus wherein the emitter and photodetector is packaged into one module. This kind of design makes the module susceptible to crosstalk since there are more paths for optical crosstalk and can be a reliability risk once an optical crosstalk path emerges. There are three possible crosstalk paths for the module: (1) Light that travel directly from the emitter to the photodetector; (2) Light that travel from the emitter to the photodetector via the path through the PCB; and (3) reflected emitter light from the glass surface to the photodetector.

In this study, the effort by ams to ensure minimal crosstalk on this packaged optical module is discussed. ams designs the package of their optical sensor module to include in the lid an optical barrier as shown in Figure 3. This barrier is composed of material that is opaque to the light emitted by the emitter and blocks the optical path directly from the emitter and the photodetector.

In this work, the package height was used as an indicator for the crosstalk performance of the optical module seen during testing. The assumption is that the substrate thickness and the lid thickness' variance is minimal and can be considered constant, thus the contributor for the difference in height is the lid glue thickness that leads to the gap in barrier height. This means that the thinner the package, the lower the crosstalk signal due to the minimal gap for the optical crosstalk path.

Three groups of devices with different yield loss related with crosstalk test were selected for this study. The following lots have yield loss for crosstalk with values 8.3 %, 21.1 % and 67.8 %. Height measurements showed that the high yield loss due to crosstalk is related to the height of the package. The full-length paper will present the crosstalk measurements and crosstalk paths in the package in detail.

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10231-109, Session PS

Optical sensors of bulk refractive index using optical fiber resonators

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Optical fiber resonators (OFRs) are demonstrated as liquid refractive index (RI) detectors. A sensor device consists of a tapered fiber for the excitation and an optical fiber as the resonator. After fiber tapering, the OFR is placed in contact with the tapered fiber in perpendicular geometry and then the sample is placed into a sample chamber after both fibers are fixed with an epoxy glue. Whispering gallery modes (WGMs) with quality factors up to 63000 and 16000 were observed from OFRs when surrounded by air and water, respectively. Spectral positions of the WGMs shift to longer wavelengths as the bulk RI of the surrounding liquid increases. To justify the detection of liquid RI changes, different concentrations of ethanol/water and ethylene glycol (EG)/water solutions are injected inside the sample chamber. Experimental characterization of these solutions is performed, as well as the analytical calculations to predict the amount of shift for ethanol/water and EG/water solutions. For EG/water solutions, the experimental results are in agreement with the calculations, however there is a discrepancy in ethanol/water experiments. This discrepancy is attributed to the slight dissolution of the epoxy glue in the presence of ethanol in the liquid environment, therefore increasing the RI of the surrounding medium more than the analytical calculations predict. In this work, robust and easy-to-fabricate OFR sensors are shown as liquid RI sensors with a high sensitivity. A lower detection limit in bulk RI sensing of 2 x 10-5 RIU (refractive index unit) is demonstrated.

10231-110, Session PS

High-resolution investigation of longitudinal modes of a GaN-based blue laser diode

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Typical emission spectra of GaN-based blue laser diodes are known to have irregular shapes. Hence, well-resolved study of their spectra may help in understanding the origin of their spectral shapes irregularity. In this paper, the spectra of a commercial GaN-based blue laser diode are studied as a function of injection current and temperature using a spectrometer with high-resolution of 0.003-nm over the spectral region 440 – 450 nm. The obtained laser spectra are used to track the longitudinal modes evolution as a function of operating currents and temperatures as well as to precisely map single mode operation. In addition, yielded laser spectra will be utilized to evaluate few parameters related to the laser diode, such as mode spacing, optical gain, characteristic temperature, threshold current, slope efficiency and wavelength rate of change with temperature and injection current.

10231-37, Session 9

Remote detection of buried explosives by fluorescent and bioluminescent microbial bioreporters *(Invited Paper)*

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Current landmine detection methodologies are not much different in principle from those employed 75 years ago, in that they require actual presence in the minefield, with obvious risks to personnel and equipment. Other limitations include an extremely large ratio of false positives, as well as a very limited ability to detect non-metallic landmines. In this lecture a microbial-based solution for the remote detection of buried landmines described. The small size requirements, rapid responses and sensing versatility of bacterial bioreporters allow their integration into diverse types of devices, for laboratory as well as field applications. The relative ease by which molecular sensing and reporting elements can be fused together to generate dose-dependent quantifiable physical (luminescent, fluorescent, colorimetric, electrochemical) responses to pre-determined conditions allows the construction of diverse classes of sensors. Over the last two decades we and others have employed this principle to design and construct microbial bioreporter strains for the sensitive detection of (a) specific chemicals of environmental concern (heavy metals, halogenated organics etc.) or (b) their deleterious biological effects on living systems (such as toxicity or genotoxicity). In many of these cases, additional molecular manipulations beyond the initial sensor-reporter fusion may be highly beneficial for enhancing the performance of the engineered sensor systems. This presentation highlights several of the approaches we have adopted over the years to achieve this aim, while focusing on the application of live cell microbeads for the remote detection of buried landmines and other explosive devices.

10231-38, Session 9

A POCT platform for sepsis biomarkers

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Infectious diseases and sepsis, as a severe and potential medical condition in which the immune system overreacts and finally turns against itself, are a worldwide problem. As a matter of fact, it is considered the main cause of mortality in intensive care. For such a pathology, a timely diagnosis is essential, since it has been shown that each hour of delay in the administration of an effective pharmacological treatment increases the mortality rate of 7%. Therefore, the advent of a POCT platform for sepsis is highly requested by physicians. Biomarkers have gained importance for the diagnosis and treatment monitoring of septic patients, since biomarkers can indicate the severity of sepsis and can differentiate bacterial from viral and fungal infection, and systemic sepsis from local infection.

The present paper deals with the development of fluorescence-based bioassays for the sepsis biomarkers and their integration on a multianalyte chip. Among the different biomarker candidates, the attention was focused on procalcitonin (PCT), C-reactive protein (CRP) and interleukine-6 (IL-6) as well as on soluble urokinase plasminogen activator receptor (suPAR) recently proposed as a very effective inflammatory marker, potentially capable of acting also as a prognostic biomarker. Starting point of this new setup was an already developed fluorescence-based optical platform, which makes use of multichannel polymethylmetacrylate chips for the detection of different bioanalytes, and the serial interrogation of the microfluidic channels of the chip. The novel proposed optical setup makes use of a suitable fluorescence excitation and detection scheme, capable of performing the simultaneous interrogation of all the channels. For the excitation part of the optical setup, a diffractive optical element is used which generates a pattern of parallel lines, for the simultaneous excitation of all the channels and for the optimization of the optical power distribution. For the detection part, an array of optical absorbing waveguides (long-pass coloured glass filters) is used, which collects the scattered light and the emitted fluorescence, filters out the excitation component, and is faced to a large area rectangular detector, for the simultaneous fluorescence detection. The implemented sandwich immunoassays comprise a capture antibody immobilized onto the surface of the chip channel and a detection antibody properly labelled with a fluorophore. Limits of detection of 2.7 ng/mL, 0.022 μg/mL, 12 ng/mL and 0,3 ng/mL were achieved for PCT CRP, IL-6 and suPAR, respectively.

10231-41, Session 9

Advanced bio/sensors: molecules, materials and light *(Invited Paper)*

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No Abstract Available

10231-42, Session 9

U-bent plastic optical fiber-based plasmonic DNA biosensor

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This study presents the development of low cost, rapid and highly sensitive plasmonic sandwich DNA biosensor using U-bent plastic optical fiber (POF) probes based on the principle of evanescent wave absorbance. A target oligonucleotide (ON) is detected by means of DNA hybridization with capture ON on a fiber probe surface and probe ON labeled with gold nanoparticles (AuNP, 40 nm). The realization of absorbance based fiber optic DNA biosensor involves choice of a suitable fiber optic probe with high absorbance sensitivity, optimum surface chemistry for immobilization of capture ON and the density of probe ON on AuNP. Plastic optical fiber (PMMA core and fluorinated polymer as cladding) was chosen due to the ease in machinability and handling. POF probes of optimum U-bent geometry with fiber and bend diameter of 0.5 and 1.4mm respectively with a high evanescent wave absorbance sensitivity were utilized [1]. The U-bent portion of the probe was decladded to expose PMMA and treated with 10% Hexamethylene diamine (HMDA) solution for 2 hours followed by 2.5% glutaraldehyde solution for 20 mins to obtain aldehyde functional groups on the PMMA surface. Subsequently, amine modified capture ONs (50 μM) were covalently immobilized on the POF probes by incubating them overnight. Subsequently, probes were treated with BSA and amine PEG to reduce non specific adsorption of target or labeled probe ONs. The probes were exposed to target ONs of different concentration ranging from pM to μM (30 μl volume) for 10 mins. The target ON treated probes were washed using DI and 0.1% tween20. Thiol modified probe ONs were conjugated to 40 nm AuNP as described elsewhere [2]. The optical setup for light intensity or absorbance measurements comprises of a commercially available LED and silicon photodetector (S150C, compact fiber photodiode, Thorlabs? USA). The U-bent POF probe is coupled between a LED and photodetector using bare fiber adapters and SMA connectors [1]. The probes were incubated in AuNP labeled probe ONs (50 μl) for 10 mins and the absorbance response was monitored real time. The rapid sensor response for detection of target ONs (pM to μM) within an assay time of 15 mins will be presented.

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10231-43, Session 9

Study of inertial hydrodynamic focusing in sheath-driven flows for lab-on-a-chip flow cytometry

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Minature flow cytometer models enable fast and cost-effective management of diseases in vulnerable and low-end settings. The single-line focusing of cell or particle samples is achieved using hydrodynamic forces in the microfluidic channels. These microfluidic focusing devices can be integrated with optical fibers to form a portable optofluidic lab-on-a-chip flow cytometry framework that can reachout to the larger community in need as part of affordable healthcare. The most common configurations among them are the single-sheath and dual-sheath rectangular micron-sized fluidic channels wherein the sample is directed through the main channel, and the surrounding sheath fluids are directed into the main channel through inlets on either side of the main channel. Most models predict the width of the focused sample stream based on hydrodynamic focusing in the low Reynolds regime (Re<<1), where the viscous forces dominate the inertial forces. However, there have been no comparative studies between the single-sheath and dual-sheath configurations related to optimization of microchannel design parameters with respect to the cell or particle size at higher Re.

In this work, we present comparative analysis of particle focusing by single-sheath and dual-sheath configurations for focusing of micron-sized cells or particles in the range 2 to 20 ?m. Analysis of the 3D Navier-Stokes equations for pressure-driven fluid flow inside microchannels in the higher Re (10 < Re < 70) laminar regime is performed using the Finite Element Method (COMSOL Multiphysics 5.1, MA, USA), and the simulated results are compared with the theoretically predicted velocity and concentration profiles. A quantitative analysis of the relative focused stream width (wf/wch) as a function of flow rate ratio (FRR = Sample flow rate/Sheath flow rate) for the two configurations is presented. These findings clearly outline the range of flow parameters and relative particle sizes that can be used for cytometry studies for given channel geometry. Besides the focusing effect as a consequence of sheath flows in the single-sheath and dual-sheath cases, the particle trajectories were simulated for particle diameters of 2 ?m, 10 ?m and 20 ?m. The particle tracing results are also compared with the experimental fluorescent microscopy results at various FRR. This is a highly predictive modeling method as it provides substantial results of particle positions across the microchannel width according to their size and FRR for single-line focusing of particles. Such information is crucial for one to engineer miniaturized flow cytometry for screening of desired cells or particles. The deviations of the results from the theoretical predictions of hydrodynamic focusing at Re <<1, are explained analytically.

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10232-1, Session 1

Diffraction limited mid infrared spectromicroscopy with a supercontinuum laser source *(Invited Paper)*

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Fourier-Transform infrared (FTIR) spectromicroscopy combines the spatial resolution of optical microscopy with the spectral selectivity of vibrational spectroscopy. At the highest performance, FTIR spectromicroscopy can be done at synchrotron sources providing diffraction limited spatial resolution. Powerful broadband light sources with continuous spectral power density in the mid infrared and diffraction-limited beam characteristics would complement the synchrotron source. In this communication, we explore the potential of a mid-infrared all-fiber supercontinuum laser source as an alternative to the synchrotron source for spectromicroscopy.

10232-2, Session 1

Mid-IR supercontinuum in a step index tellurite fibre operating between 1 and 5 µm

Paul Froidevaux, Clément Strutynski, Arnaud Lemière, Bertrand Kibler, Frédéric Désévédavy, Jean-Charles Jules, Pierre Mathey, Pierre Béjot, Franck Billard, Olivier Faucher, Frédéric Smektala, Univ. de Bourgogne (France)

Development of broadband supercontinuum (SC) fibered laser sources in the mid-infrared (MIR) is widely studied since the last two decades for its high application potential in various fields such as spectroscopy, defense, medical science and others. Such optical systems were originally investigated in silica, but were rapidly adapted to alternative materials. Among them, tellurite glasses appear to be a good compromise because of their 1-6 µm transparency widow, high nonlinear optical properties (10 times that of silica) and moderate dispersion (bulk ZDW around 2 µm). However, at the moment, few studies report spectral broadening spreading further than 3 µm in tellurite fibers, and even fewer present SC reaching their multi-phonon edge located around 5 µm. We report here a study on the manufacturing of step-index tellurite, germanate and germanate-tellurite fibers including their linear and nonlinear characterizations. Three different step-index profiles with varying refractive index difference (?n = 0.051, 0.086 and 0.128) are explored, in particular by combining the built-in casting and rod-in-tube techniques for fiber fabrication. Fibers with large core (40 µm) and small cores (between 3 and 5 µm) are drawn. The background losses for large-core step-index fibers are around 1 dB/m between 1 and 3 µm. The chromatic dispersion of the small core fibers as a function of core diameter is discussed, and numerical simulations based on the generalized nonlinear Schrödinger equation are performed to explore supercontinuum generation in these fibers. Fibers exhibiting a flat dispersion with two ZDWs are then experimentally tested. The pumping of this fibers with an OPO near their ZDW allow the generation of a supercontinuum in the infrared with a good agreement between numerical simulations and experimental results. The maximum extension obtained allows to fully cover the atmospheric 3-5 µm window.

10232-3, Session 1

Development and characterization of highly-nonlinear multicomponent glass photonic crystal fibers for mid-infrared applications

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We present a detailed characterization of multicomponent glass photonic crystal fibers (PCFs) suitable for mid-infrared applications. The paper covers the fiber design, discusses fiber manufacturing, presents measurements of fiber dispersion and nonlinearity, adds the simulation model correction and proposes applications, especially supercontinuum generation. The dispersion profile estimation is the core of our work and is verified by a comparison of two precise measurement techniques, one based on a Mach-Zehnder interferometer and one utilizing a commercially available component analyzer (LUNA® OVA5000). Furthermore, the dispersion profile is related to calculations based on a scanning-electron microscope (SEM) image of the drawn fiber.

As a continuation of our previous work focusing on multicomponent glass PCFs with a hexagonal inner structure, we have designed suspended-core PCFs with a core diameter on the scale of a few microns, leading to increased nonlinearity. Selected fiber designs were fabricated according to a simulation model by the stack-and-draw technique. Post draw SEM analysis provided the real structure profile, which was compared to the simulation model and used as an input for the dispersion calculation. The targeted zero dispersion wavelength (ZDWL) for the first suspended-core PCF was 1060 nm where ytterbium-based lasers provide high peak powers. This regime was chosen to serve as a base for a near-/mid-infrared supercontinuum source. For the second suspended-core PCF, the glass composition included a higher content of silica, and thus a significant shift in ZDWL is expected.

The dispersion measurement setup was based on a Mach-Zehnder interferometer with focusing optics specially designed to provide low-loss coupling to very small core diameters. The influence of optical elements on the measurement results and broadband coupling into PCFs is discussed. The wavelength range of this setup was 700-2400 nm. This dispersion measurement output was verified on a standard PCF (ESM-12B, Thorlabs), which has well a known ZDWL at 1060nm. We prove in our measurements that we are able to determine ZDWL with accuracy better than 10 nm for the fibers studied. A second ZWDL measurement LUNA device was used with the same focusing optics. Results from both measurements are compared.

Based on the measurement results, we obtained the necessary feedback for our fiber-design simulation where we proved that one critical factor is the accuracy of the equation used for the index of refraction of the glass. This parameter must be extremely precise to enable proper dispersion profile estimations and to calculate the ZWDL with a reasonable precision of less than 10 nm. Manufacturing tolerances and imperfections will be discussed in the full paper.

10232-4, Session 1

Spectral properties of thulium and holmium doped optical fibers for fiber lasers around 2 micrometers

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Thulium-doped and holmium-doped fibers have been widely investigated because of their luminescence properties making them suitable for fiber lasers operating around 2 microns. Such fiber lasers have been recently developed for variety of medical applications, wireless communication, fiber sensors, spectroscopy, machining of polymeric materials and others.

In this contribution we present experimental results of characterization of the developed holmium-doped and thulium-doped silica-based optical fibers. Their cores were doped with Al2O3 (GeO2-Al2O3) and with rare earth elements in concentration from 1000 ppm to 10 000 ppm. The fibers were fabricated by the modified chemical vapor deposition and solution doping methods. Prepared fibers were characterized in terms of their spectral attenuation, fluorescence lifetime, refractive index profile, and especially performance in fiber laser. The influence of rare earth elements concentration on laser performance will be shown and trends will be discussed.

Acknowledgement

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10232-5, Session 1

Fe2+:ZnSe saturable absorber mirror passively Q-switched fluoride fiber laser at 2.8 ?m

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Based on the vacuum evaporation method, a mid-infrared saturable absorber mirror (SAM) was fabricated by coating Fe2+-doped zinc selenide film on a gold mirror. By employing the perpared Fe2+: ZnSe SAM, we demonstrated a passively Q-switched Er3+-doped ZBLAN fiber laser at the wavelength of 2.8 ?m. Stable Q-switched pulses with pulse duration of 0.8 ?s was obtained. Our results demonstrate that Fe2+: ZnSe SAM is a promising device for high power pulse generation in mid-infrared fiber lasers.

10232-6, Session 2

Fiber Bragg filters for laser and multicore fibers *(Invited Paper)*

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Fiber Bragg gratings have widespread applications in security, information, structural health monitoring, and biophotonics. In Telecom, FBG inscription has reached a high level of maturity, but remains limited to germanium doped standard photosensitive single mode fibers. Special applications, for example filtering in light harvesting fibers or resonator mirrors for fiber lasers have to deal with special aspects which make the realization of FBGs a challenging task. One aspect is the extended wavelength range of these applications from the visible to the infrared. Another aspect is the increasing demand to inscribe fiber Bragg gratings in non-photosensitive germanium-free fibers. Therefore, novel concepts of photosensitivity are required. Finally, to increase the amount of guided light the size of the fiber core has also to be increased. This goes along with multimode operation and prevents good filtering properties of the gratings. In this case, special inscription techniques like the chirped-phase mask interferometer can be applied to improve filtering performance.

10232-7, Session 2

Reflectivity of superimposed transient gratings in self-swept fiber lasers

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The recently observed laser wavelength self-sweeping is known for its large sweeping range up to tens of nanometers, single- or few-longitudinal mode operation and self-pulsing output [1-5]. The self-sweeping can be explained by spatial hole burning along the active fiber. The spatial hole burning cause also weak refractive index modulation [6-7]. Self-swept fiber lasers recently attained attention thanks to its practical applications in laser spectroscopy and fiber sensor systems as well as revealing physical insight view into important laser physics phenomena, e.g., the origin of self-Q-switching regime and longitudinal mode-instabilities in fiber lasers.

We present evaluation of the reflectivity of superimposed transient fiber Bragg gratings (FBG) using a numerical model of fiber laser with refractive index gratings build-up. In contrast to single refractive index grating demonstrated earlier [6-7] we present more realistic case of several superimposed gratings with damped modulation depth. We show that the 100 % reflectivity and thus sudden enhancement of the cavity Q-factor can be easily achieved despite small modulation depth of the gratings. The differences of reflectivities of the single FBG and of the multiple superimposed damped FBGs are discussed. This work was supported by the Czech Science Foundation, project No. 16-13306S.

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10232-8, Session 2

Bandpass transmission filters based on phase shifted fiber Bragg gratings in microstructured polymer optical fibers

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Phase-Shifted fiber Bragg gratings (PS-FBG) in silica fibers have been demonstrated during the last decade as attractive very narrow filters for a variety of applications in telecommunications [1]. Very recently published papers report PS-FBG applications also in the microwave photonics field, such as tunable bandstop-to-bandpass microwave photonic filters, which opens new perspectives for these devices [2].

Polymer optical fibers (POFs) have several advantages over silica fibers, such as a larger elongation before breakage, a higher thermo-optic coefficient, and a lower Young's modulus. These advantages will provide a broad tuning range either straining or heating the fiber, and easy handling due to its low stiffness and therefore, lower installations cost. Although the product of bandwidth and channel length is reduced and they are suitable for in-building and short range applications, the introduction of the new polymer called CYTOP [3] with reduced losses leads to new promising applications for POF.

FBGs in silica fibers is a very mature filtering technology both for telecommunications and sensors [4] since a large variety of high performance FBGs can be fabricated by creating a UV light induced periodic variation in the refractive index of the fiber core. However, since the first polymer FBG reported in 1999, very promising devices have been demonstrated, mostly for measuring strain and temperature [5, 6], also using microstructured [7] or CYTOP [8] fibers. Despite of this, POF gratings are still under research; high quality gratings fabrication require photosensitive fibers; so far great advances have been done both in doped and undoped fibers, but grating time stability is still an issue.

The literature only provides a single report on a phase-shifted FBG in POFs, which was for use at THz frequencies [9] by using a point-by-point FBG fabrication method. In this contribution we report on the fabrication of novel bandpass transmission filters based on PS-FBGs in microstructured polymer fibers at telecom wavelengths. The phase mask technique is employed to fabricate several superimposed gratings with slight different periods in order to form Moiré structures with a single or various ϖ phase shifts along the device. Very narrowband transmission filters are demonstrated and experimental characterization of the devices under strain and temperature variations is provided.

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10232-9, Session 2

Impact of thermal pretreatment on preforms for fast Bragg gratings inscription using undoped PMMA POFs

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In this work, improvements in the photosensitivity of undoped POFs, where there was a well-defined pre-annealing of the preform, were reported. We have noticed that with non-annealed preforms, the fiber photosensitivity is lower. The fibers from preforms with specific thermal pre-treatment allow us to achieve less FBG inscription times than fibers with no well-defined annealing, obtaining at the same time stable FBG sensors with high quality. We also addressed the actual influence of annealing on the strain sensitivity of the fibers prior and after FBG inscription, showing that the fiber produced from a preform with well-defined pre-annealing did not produce any significant difference. Some important parameters were considered such as drawing tension and water content, where using fibers drawn in different tensions give us a similar FBG inscription time. We can also conclude that a fiber drawn from a preform which had not a specific process of annealing, it will include a slight amount of water inside of preform and will affects the fiber performance.

10232-10, Session PS

Chirped polymer optical fiber Bragg grating sensors

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We report chirped fiber Bragg gratings (CFBGs) photo-inscribed in undoped PMMA polymer optical fibre (POF) for the first time. The chirped polymer optical fiber Bragg gratings (CPOFBGs) were inscribed using an UV KrF excimer laser operating at 248 nm. The rectangular gauss laser beam was expanded to 25 mm in horizontal direction along the fiber core by a cylindrical lens, giving a total of 25 mm grating length. A 25 mm long chirped phase mask chosen for 1550 nm grating inscription was used. The laser frequency was 1 Hz with an energy of 5 mJ per exposure, exposing few shots for each grating inscription. The reflection amplitude spectrum evolution of a CPOFBG is investigated as a function of the applied strain and temperature. Also, some results regarding to group delay are collected and discussed. These results pave the way to further developments in different fields, where POFs could present some advantages preferably replacing their silica counterparts.

10232-13, Session PS

Analysis of optical properties of special fibers of polydimethylsiloxane (PDMS) depending on the different methods of mixing PDMS and curing agent

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The authors focused on the problems of measurement of attenuation and homogeneity of special fibers of polydimethylsiloxane (PDMS) depending on three different procedures for mixing PDMS and curing agent. We used a two-component elastomer Sylgard 184. For mixing was used a defined ratio of 10:1 for PDMS, which was determined based on the datasheet. Curing of samples took place in a heat box at a constant temperature of 80 °C ± 3 °C. Three procedures were defined for mixing PDMS and curing agent: manual, using a laboratory shaker and ultrasonic baths. For each method of mixing was carried out a total of 25 samples. The test samples have a defined shape in the form of a cylindrical waveguide with a diameter of 10 mm and a length of 50 mm. The whole process of production of cylindrical waveguides applied in the protective vacuum box. To verify the homogeneity of the samples were divided into 5 mm sections, measured was the attenuation constant in both directions. As a source of radiation was used LED (Light Emitting Diode) with a wavelength of 470 nm. The outcome of this study is the evaluation of the quality waveguides by the size of the total attenuation and the attenuation constant for analysis of spreading out inhomogeneities depending on the procedure of mixing PDMS and curing agent. The analysis performed with regarding the use of PDMS for its optical properties.

10232-15, Session PS

Making compact bundle fiber for laser-assisted surgery

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Treatment surgery using laser in the medical field, using the optical fiber. When utilizing the existing optical fiber, can only forward or side emission, it was difficult to radial emission. In order to solve this problem, we had developed a bundle type optical fiber(bundle fiber) that can be radial emission. However, the outer diameter of the developed bundle fiber is large, and non-conforming to immediate use in the human body. The purpose of this study is compact (less than outer diameter 1.2 mm) to develop a bundled optical fiber in order to overcome these drawbacks.

10232-26, Session PS

Measurement of spectral characteristics and CCT mixture of PDMS and the luminophore depending on the geometric parameters and the concentration of the samples of the special optical fibers

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White light is produced by a suitable combination of spectral components RGB (colors) or through exposure excitation of blue light (the blue component of light). This blue part of the light is partly and suitably transformed by luminophore so that the resulting emitted spectrum corresponded to the spectral characteristics of white light with a given chromaticity correlated temperature (CCT). This article deals with the measurement of optical properties of a mixture polydimethylsiloxane (PDMS) and luminophore, which is irradiated by the blue LED (Light-Emitting Diode) to obtain the white color of light. The subject of the investigation is the dependence of CCT on the concentration of the luminophore in a mixture of PDMS and different geometrical parameters of the samples. There are many kinds of PDMS and luminophore. We used PDMS Sylgard 184 and luminophore-labeled U2. More accurately Yttrium Aluminium Oxide: Cerium Y3Al5O12: Ce. From the analyzed data, we determined, which mutual combinations concentration of the mixture of luminophore and PDMS along with the geometric parameters of the samples are suitable for illumination, while we get the desired CCT.

10232-27, Session PS

Enhanced linear photonic nanojet generated by core-shell optical microfibers

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The spatial resolution of standard optical microscope is practically limited due to diffraction of light. Recently, microsphere-assisted super-resolution optical imaging is proposed as a simple technique for visualizing nano-scale features in the far-field system. The super-resolution capability of such microspheres is introduced by their extreme sharp focusing characteristics. The observation and demonstration of super-resolution imaging include the employments of silica microspheres, high-index microspheres, microspheres in the confocal mode, microsphere locomotion and dielectric slab with microspheres. The optical imaging of nano-scale targets obtained through microspheres in the visible light region has been proved to exhibit features with size smaller than 100 nm. However, the operation of photonic nanojets generated by microspheres is a challenging work because the management and fixation of isolated microspheres on the sample surface have some technical difficulties in practice. Furthermore, the imaging range of microsphere is small since the field of view depends on the microsphere diameter. Instead of microspheres, we consider the design and fabrication of core-shell optical microfiber for the generation of linear photonic nanojet. Considering the photonic nanojet formation from core-shell optical microfibers, the metallic shell is proposed to enhance the nanojet intensity.

The generation of linear photonic nanojet using core-shell optical microfiber is demonstrated numerically and experimentally in the visible light region. The refractive indices of the dielectric microfiber and gold shell are 1.46 and 1.46+1.954i. The refractive index of the surrounding medium is 1 (air). A monochromatic light beam with wavelength 532 nm propagates from the left side of microfiber. The power flow patterns for the core-shell optical microfiber are calculated by using the finite-difference time-domain method. The focusing properties of linear photonic nanojet are evaluated in terms of length and width along propagation and transversal directions. In experiment, the silica optical fiber is etched chemically down to 6 ?m diameter and coated with metallic thin film by using glancing angle deposition. We show that the linear photonic nanojet is enhanced clearly by metallic shell due to surface plasmon polaritons. The large-area super-resolution imaging can be performed by using a core-shell optical microfiber in the far-field system. The potential applications of this core-shell optical microfiber include micro-fluidics and nano-structure measurements.

10232-28, Session PS

Realization of optical multimode TSV waveguides for Si-Interposer in 3D-chip-stacks

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The continuously increasing demand for higher bandwidth and evolution towards to 5G makes the application of an optical chip to chip interconnect system conceivable. Based on the assumption of a 3D-chip-package an essential ingredient of such a system is the availability of a vertical interconnect. Usually, for electrical communication copper filled through-silicon-vias (TSV) are used. To integrate an optical communication network in a 3D-chip-stack vertical optical TSV interconnect is required. Here, we present the fabrication of an optical polymer based waveguide in TSVs proved on waferlevel using SU-8 as core and SiO2 as cladding.

Optical connection has the potential to outperform copper-based connections in terms of bandwidth at the cost of more complexity due to the required electro-optical and opto-electrical conversion. Once converted, the transmission distances in the optical domain are far less critical than in the electrical domain. The advantage of optical interconnects as optical waveguides or fibers is well established for long distance communication. The continuously increasing demand for higher bandwidth pushes the breakeven point for a profitable operation to shorter distances. While the required effort for the electrical/optical and vice versa conversion makes it hard to envision an on-chip optical interconnect, a chip-to-chip optical link appears conceivable. Until this will have been realised, one has to consider a 3D-chip package based on silicon-interposers. In general, the interposer offers the potential advantage to realize electro-optical transceivers on affordable expense by specific, but not necessarily CMOS technology.

We investigated the realization and characterization of optical interconnects as a polymer based waveguide in high aspect ratio TSVs proved on waferlevel.

To guide the optical field inside a TSV as optical-waveguide or fiber, its core has to have a higher refractive index than the surrounding material. Comparing different material / technology options it turned out that silicon dioxide (ncl = 1.4525 at 850 nm) is a perfect candidate for the cladding, because it can be manufactured as a very conformal layer by a well-known and controllable process, thermal oxidation. In combination with SiO2 as the adjacent polymer layer, the negative resist SU-8 is very well suited as waveguide-material (nc = 1.56) for the core.

We demonstrate a waferlevel proved filling process for optical TSV (diameter 10 - 40 μm in 200 – 380 μm thick Si interposer). The TSV

waveguide concept requires a SiO2 surface as waveguide cladding. To realize it, the cylindrical TSVs were etched by an optimized deep reactive ion etching (DRIE) through the substrate. Afterwards, a 2 μm SiO2 cladding is grown by thermal oxidation of Si. Next, the wafer-backside is covered with a temporary bonded PDMS-membrane. The SU-8 resist acting as waveguide-core-material is deposited on the wafer-frontside as a thin-film by spin-coating. Homogeneous filling of TSVs is achieved by vacuum and temperature. Next a maskless exposure of the SU-8 layer to UV-light is performed in order to achieve a cross-linked SU-8 inside the TSV.

The process resulted in a defect-free filling of waveguide TSVs with SU-8-core and SiO2 cladding up to AR 20:1 and losses less than 3db.

10232-29, Session PS

All-polymeric photonic waveguides and ring resonators for optical integrated circuits system

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In this paper, we are reporting an experimental work on the design and fabrication of the polymeric passive all-optical waveguides, and optical microcavities based on very interesting and inexpensive laser beam direct write lithography (LBDW) technique are reported. This technique is simple yet robust and promising method for fabrication of the complex polymer optical devices. A continuous wave (CW) laser operating at 442 nm with a typical optical output power 120 mW is used in the laser beam direct writing system. These all-optical devices have been fabricated based on optical ORMOCORE and ORMOCLAD negative photoresist which is inorganic-organic hybrid polymer. These optical materials are very low losses at telecom wavelengths (1550 nm and 1300 nm), well controlled refractive indices, and ease of processing, good thermal stabilities, and good adhesion on a wide range of substrates. Optical characterization of these fabricated optical devices is shown to ensure suitability for implementation in optical integrated circuits applications.

10232-30, Session PS

Numerical simulation analysis of gain and noise figure using various pumping direction in single- and multiple stage EDFA systems

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In this study, we numerically investigated single, double and triple stages of Erbium-doped fiber amplifier (EDFA) systems with single-pass (SP) and double-pass (DP) configurations to obtain higher gain and lower noise figure (NF) values. We used an input signal -35 dBm at the wavelength of 1550 nm and the total pump power 24 mW at the wavelength of 1480 nm. We simulated each EDFA system in Matlab with Giles and Desurvire model using various pumping configurations. Besides the single-pass configurations, we proposed two different double-pass configurations for double-stage EDFA and four different double-pass configurations for triple-stage EDFA. Using various pumping direction schemes, we analyzed and compared the physical properties of each simulated EDFA configuration.

10232-31, Session PS

Anti-reflection and polarizing photonic structures for high power fiber applications

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We investigated behaviors of 1D binary diffraction gratings milled on optical fiber facets. The aperiodic rigorous coupled wave analysis, the Fourier modal method and the finite-difference time-domain numerical methods were used to compute the reflectivity of the investigated structures. Only sub-wavelength structures were considered to suppress higher diffraction orders. Focused ion beam was used to fabricate an optimized grating directly on the large-mode area fiber facet. One of the gratings was tested in a thulium-doped fiber laser where it acted as a low reflectivity polarizing output mirror. The slope efficiency and laser beam quality parameter were conserved while lasing threshold slightly increased.

10232-32, Session PS

Microsensors of liquid based on capillary self-assembly micropillar fabricated by femtosecond laser printing

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Capillary force exists widely and always is treated as harmful in microfabrication because it may cause undesired distortion or even destruction of micro/nanostructures. But, in the other hand, once if the capillary force (Fc) can been controlled flexibly, it will be changed from harm to benefit. Many researches have been done in the utilizing of Fc as driving force in self-assemble of micro/nanostructures. [1, 2] However, there is a little work in taking advantage of it to construct sensors. Here, by combining capillary force self-assembly with femtosecond laser printing, we introduce a method to distinguish liquids based on the different self-assembly results of micropillars array. Micro pillars, whose diameters are 760 nm, are printed by direct laser writing (DLW) firstly. If these polymer pillars are upright after development, they will present structure colors which will disappear if they collapse. Because the self-assembly is a result of the competition between standing force (Fs) and capillary force (Fc), the collapsed patterns will stand-up again when they were immersed in liquid again and assembled into different patterns due to the properties of liquids (e. g. surface tension and contact angle). This method to distinguish liquid features flexible and may be developed into visible to the naked-eye without any equipment which may be useful in some applications. Considering fs-DLW can printing microstructures in microchannels directly, [3, 4] this liquid sensors may also find unique applications in microfluidic.

10232-11, Session 3

Realisation of optically resilient fiber tip 3D microoptics

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Optical fibers gain more and more attention in the fields of data transfer, sensors and advanced light generation, thus an integration of functional optical elements in a fiber based systems becomes increasingly prominent task [1]. This presentation is dedicated to an additive 3D femtosecond laser microfabrication of polymer structures for direct light shaping both propagating out of or coupled into the single mode optical fiber. These include microlenses, microaxicons and spatial phase plates. Additionally such mounted elements can be combined as multicomponent 3D monoliths for enhanced functionality [2, 3], they are tested experimentally.

In contrast to standard lithographic techniques, 3D femtosecond laser lithography can be employed for processing a wide array of materials, including otherwise non-processable (non-photosensitized) polymers [4]. One of such materials is hybrid or hybrid organic-inorganic zirconium containing SZ2080 that displays many favourable qualities such as optical transparency and low shrinkage [5]. Here we provide notes on peculiarities 3D laser lithography of the pure SZ2080 for microoptics. It is investigated how it compares to a photosensitized one by its fabrication throughput, optical properties (transmission spectra and surface roughness), mechanical strength (structure survival rate and adhesion to the substrate) as well as other.

Optical resiliency of microoptical elements created by this technology is investigated and their feasibility in applications reliant on high light intensities is studied. As expected, the most resistant material was found to be non-photosensitized SZ2080. Microlenses produced out of it can withstand peak intensities of 515 nm 300 fs 200 kHz laser in range of GW/cm^2 within minutes to hours [6]. Such results ties well with earlier findings showing that optical damage threshold of pure materials films are in fact significantly higher than that of a photosensitized material [7]. Additionally, CW 405 nm laser operating at intensity of 86.6 W/cm^2 cannot damage microoptical elements produced out of SZ2080 in pure and photosensitized compositions even after tens of hours of continuous exposure. Resiliency comparison with microoptical elements of standard lithographic materials such as Ormocer and SU8 is carried out as well. These results prove that the pure SZ2080 is a candidate material for high light intensity applications at microscale.

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10232-12, Session 3

Optical fiber-based frequency references

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This work is oriented towards an effort to preparation, filling and testing of optical frequency references based on hollow-core photonic crystal fibers. This type of references intended for frequency locking of accurate laser sources overcomes difficulties of classic bulky glass-made absorption cells and it brings an opportunity to reduce volume and mass of the laser stabilization setup. Crucial step in hollow-core photonic crystal fiber-based reference development is a careful preparation of the fiber itself (cleaving of the fiber ends, splicing of the microstructured fiber to standard type of fiber/or equipment of the fiber with fiber connectors with minimalization of optical losses) and especially filling of the fiber inner structure with appropriate absorption media with ensuring of non-contaminant approach. This contribution expresses recent progress in microstructured fiber-based optical frequency references development and it presents the results from measurement of achievable optical and spectral properties of manufactured fiber-based cells.

10232-14, Session 3

Fabrication of long linear arrays of plastic optical fibers with squared ends for the use of code mark printing lithography

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Two dimensional code marks are widely used for obtaining various properties of industrial products by easily and quickly reading the marks. In productions of liquid-crystal-display (LCD) panels and others, marks containing production numbers and fabrication conditions are printed in the production process, and used for quality managements. In such cases, considerably small marks are printed by lithography using a specialized code-mark numbering exposure system. A typical code mark is composed of 44?44 square dots and has a size of approximately 2 mm square. The conventional numbering exposure systems use lamp projection exposure or laser beam delineation, and prices of the systems are very high. For this reason, development of a new low-cost exposure system using light emitting diodes (LEDs) is expected. In the new system, code marks are printed by projecting a square plastic optical fiber matrix ends, and assigning bright or dark by switching on or off the LEDs supplying exposure light to each fiber. The feasibility of the system was demonstrated in the past research using 100 LEDs with a central wavelength of 405 nm, a 10?10 matrix of optical fibers with 1 mm square ends, and a 10X projection lens [1]. However, it was difficult to fabricate a more precisely arrayed optical fiber matrix using fibers with a finer diameter of 500 ?m. For this reason, a new method for fabricating large-scale linear arrays of fibers with squared ends is newly developed here.

In the conventional method, 1-mm fibers were squared one by one, and they were adhered and bound later. In comparison, in the new method, a lot of 500-?m fibers arranged in a linear gap of an arraying instrument are simultaneously squared by heating them on a hotplate. Therefore, times and labours were drastically saved. In addition, size homogeneity and light leaks at the squared parts were greatly improved. The heating temperature was kept at 120ºC, because the fibers did not become square at lower temperatures, and the size fluctuation became large at higher temperatures. The heating time was kept for 7 min for obtaining the most squared cross section profiles. As a result, linear arrays of up to 40 fibers were successfully fabricated. Fiber sizes were homogeneous within 496±4 ?m. In addition, average light leak of 10 fibers was improved from 34.4 to 20.2% by adopting the new method in place of conventional one by one squaring method. It is considered that this is because clads between neighboured fibers were remained as they were in the case of the new method, though clads directly touching the heated squaring instrument were broken and peeled off. Square fiber matrices necessary for printing two dimensional code marks will be fabricated by piling the newly fabricated linear arrays up.

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10232-16, Session 4

Enhancement of pump absorption efficiency by bending and twisting of double clad rare earth doped fibers

(Invited Paper)

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High-power operation of fiber lasers was enabled by the invention of cladding-pumping in a double-clad fiber structure. Because of existence of so called skew rays in the inner clad of the fiber, pump absorption saturates along the fiber and pumping becomes inefficient. First studies of pump absorption efficiency enhancement were focused on fibers with broken circular symmetry of inner cladding eliminating skew rays [1,2]. Later, techniques of unconventional fiber coiling were proposed [3]. However, theoretical studies were limited to the assumption of a straight fiber. Even recently, the rigorous model accounting for fiber bending and twisting was described [4-6]. It was found that bending of the fiber influences modal spectra of the pump radiation and twisting provides quite efficient mode-scrambling. These effects in a synergic manner significantly enhances pump absorption rate in double clad fibers and improves laser system efficiency.

In our contribution we review results of numerical modelling of pump absorption in various types of double-clad fibers, e.g., with cross section shape of hexagon, stadium, and circle; two-fiber bundle (so-called GTWave fiber structure) a panda fibers are also analyzed. We investigate pump field modal spectra evolution in hexagonally shaped fiber in straight, bended, and simultaneously bended and twisted fiber which

brings new quality to understanding of the mode-scrambling and pump absorption enhancement. Finally, we evaluate the impact of enhanced pump absorption on signal gain in the fiber.

These results can have practical impact in construction of fiber lasers: with pump absorption efficiency optimized by our new model (the other models did not take into account fiber twist), the double-clad fiber of shorter length can be used in the fiber lasers and amplifiers. In such a way the harmful influence of background losses and nonlinear effects can be minimized.

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10232-17, Session 4

An 8-channel wavelength demultiplexer based on photonic crystal fiber

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The photonic crystal fiber (PCF) is a unique structure based on microstructured formation of high and low refractive index materials. Usually the high-index background material is pure silica while the low-index areas consist usually of an array of air holes along the fiber length.

Several advantages of PCF in comparison to optical fibers and conventional waveguides have been demonstrated previously. The main benefit of a design demultiplexer based on PCF is the lower coupling length value obtained in the case of closely coupled cores.

Three different techniques have been demonstrated capable to couple light between close cores in PCF structures. The first technique employed was by replacing some air-holes zones with pure silica along the PCF axis. The second technique used was by designing a PCF with a different periodic structure of air-holes between planes xz and yz and the third technique used was by integrating small air-holes in the PCF structure which allows controlling the light coupling between close cores with fixed distances.

We propose a novel 8-channel wavelength demultiplexer based on PCF structures that operate at 1530nm, 1535nm, 1540nm, 1545nm, 1550nm, 1555nm, 1560nm and 1565nm wavelengths. The new design is based on replacing some air-holes zones with silicon nitride and lithium niobate materials along the PCF axis with optimization of the PCF size. The reason of using these materials is because that each wavelength has a different value of coupling length. Numerical investigations were carried out on the geometrical parameters by using a beam propagation method (BPM). Simulation results show that the proposed device can transmit 8-channel that works in the whole C-band (1530-1565nm) with low crosstalk ((-16.88)-(-15.93) dB) and bandwidth (4.02-4.69nm). Thus, the device can be very useful in optical networking systems that work on dense wavelength division multiplexing (DWDM) technology.

In this work, we present a 1x8 wavelength demultiplexer in PCF structure that divides eight channels in the C-band range with a spacing of 5nm between channels. The operating wavelengths are: 1530nm, 1535nm, 1540nm, 1545nm, 1550nm, 1555nm, 1560nm and 1565nm. Thus, this device can be very useful for transmitting a wide information in DWDM systems.

10232-18, Session 4

Moving chirped soliton under laser pulse interaction with gold nanorods

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We investigate splitting and self-trapping of the femtosecond pulse by nanorods reshaping front under optical radiation propagation in a medium containing gold nanorods. We take into account multi-photon absorption of laser radiation by nanorods, and time-dependent nanorod aspect ratio changing due to their re-shaping because of the laser energy absorption. On the basis of computer simulation we demonstrate appearance of slowing down soliton and superluminality effect simultaneously for various sub-pulses which form from incident Gaussian un-chirped pulse. These sub-pulses possess chirp and soliton shape which differs from classical soliton of nonlinear Schrödinger equation.

10232-19, Session 4

Three-dimensional light bullets in anisotropic microdispersive media

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Tree-dimensional light bullets in Kerr media are known to be unstable. Different schemes were proposed to overcome this obstacle. One of them is to use a nonlinear parametric interaction. Such a type of interaction can be achieved in anisotropic micro-dispersive media where spatial dispersion is of great importance. These media allow us to reach a simultaneous approximate fulfillment of group and phase matching.

To study the general (3+1) D case we apply both an approximate analytical approach and numerical simulations. We suggest that nonlinear refraction manifests itself earlier than diffraction and dispersion.

Both the general (3+1)D case and axial-symmetry case are studied. With the help of averaged Lagrangian method an analytical solution in (3+1) D case is derived provided that the fixed relation between the negative coefficients of the group velocity dispersion on both harmonics holds.

We demonstrate that a spatiotemporal light bullet propagates for at least 300 nonlinear lengths in anisotropic media at second harmonic generation. We also consider the pulse mode of generation of the second harmonic in the gradient focusing wave guide under condition of positive dispersions of the group velocities on both harmonics.

10232-20, Session 4

Engineering ultra-flattened normal dispersion photonic crystal fiber with silica material

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The tailoring of the group velocity dispersion (GVD) of an optical fiber is critical in many applications as in high-speed optical communication systems because of its influence on the bandwidth of information transmission, successful utilization of nonlinear optical properties for supercontinuum generation, wavelength conversion and harmonic generation via stimulated Raman scattering ...

In supercontinuum generation, the spectral broadening as pulse propagates along the fiber in a normal dispersion regime is a result of an interplay between many nonlinear effects such self-phase modulation (SPM), self-steepening and intrapulse Raman scattering. Due to the strong dependence of those nonlinear effects and the dispersive characteristics, a tailor shape of the total dispersive curve is necessary to obtain a broadband output supercontinuum spectrum. As a photonic crystal fiber (PCF) is reported as promising candidate to control dispersion because of its large freedom degrees which offers a variety of possible geometries, this open up possibilities to design flattened dispersion fibers over a wide range of wavelengths and generating a supercontinuum with a flat spectrum over this range.

Therefore, the realization of ultra-flattened dispersion PCFs by a relatively simple method is still a challenge; complicated design methods have been exploited, such as changing the diameter of the air holes belonging to the first two or three inner rings, doping additional materials in the central part of the silica core, modifying the circular air holes into other shapes, selectively filling the PCF with liquids, designing a hybrid core region with three-fold symmetry for the fiber, assembling additional defected air holes in the central core region, or combining two or more of these methods.

In this work, we propose a design of ultra-flattened photonic crystal fiber, by using the influence of changing the diameter of the air holes belonging to the first two or three inner rings of the cladding on the dispersion curve, we reduce and tailor the dispersion curve of the proposed PCF geometry over a large wavelengths band. It is composed of only four rings, hexagonal structure of air holes and silica as background of the solid core.

The proposed PCF is analyzed using the vectorial finite element method (FEM) using the adequate perfect matched layer (PML), PCF is numerically modeled for determining its characteristics as group velocity dispersion (GVD) and confinement loss.

In the conception, the ratio parameter (di/?) of the distance between air holes (pitch) and the air holes diameters (d) of the rings allows the control of the dispersion curve; the balance between material dispersion and waveguide dispersion of the proposed geometry allows the choice of the chromatic dispersion regime, minimizing its value, and also keeping it on a large wavelengths band.

In the geometry modeling, the variation of the air holes diameters of the first and the second rings minimizes the chromatic dispersion value of the fiber. The variation of the pitch allows tailoring the curve of dispersion with the same regime on a large spectral domain.

As a result, we present structures with broadband flat normal dispersion on many wavelengths bands useful for several applications. We obtain flat normal dispersion over 1000 nm broadband flat normal dispersion below -7 [ps/nm.km] from 1000 nm to 2000 nm wavelengths, and ultra-flat near zero normal dispersion below -0.2 [ps/nm.km] over 250 nm from 1075 nm to 1325 nm wavelengths dedicated to supercontinuum generation with 1300 nm laser sources.

The modeled photonic crystal fiber would be valuable for the fabrication of ultra-flattened-dispersion fibers, and have potential applications in wide-band high-speed optical communication systems, supercontinuum generation and many other applications.

10232-21, Session 5

Spectroscopic studies of the influence of the aluminum concentration in heated Yb-doped optical fibers

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The generation and amplification at wavelengths longer than 1100 nm is not straightforward when using Yb-doped optical fibers, since light emission occurs preferentially in the region of 1020 nm - 1100 nm with a maximum at 1030 nm. One well known approach is to heat the Yb-doped fiber up to temperatures above 100 °C. This increases the re-absorption in the lower emission band and also enhances at the same time the emission at longer wavelengths. Consequently, heating allows to extend the spectral gain-region of Yb-doped fibers by at least 60 nm up to 1160 nm. However, the drawback of this method is that it results in a shorter lifetime of the fiber, since heating damages the polymer-coating. Moreover, such a laser has a reduced overall efficiency, due to heating, isolation and heat removal issues.

It has been reported, that at the presence of an aluminosilica host matrix efficient laser activity at around 1150 nm can be achieved by heating the Yb-doped fiber to only 60 °C. In this work we conduct spectroscopic studies of the influence of the aluminum concentration to heated Yb-doped fiber. The fibers are drawn in our in-house fiber drawing tower. The preforms are produced by the sol-gel-based granulated silica method which allows us to vary the aluminum as well as the ytterbium concentrations within a large range. The fibers are investigated with respect to their absorption and emission spectra as well as their performance in a laser system at wavelengths higher than 1100 nm.

10232-22, Session 5

Broadband infrared emission from Er/Nd/Bi/Al doped fibers produced by the sol-gel-based granulated silica method

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Driven by the high potential of micro-structured and specialty optical fibers several new preform production techniques have been developed. Over last years we have devoted our attention to the granulated silica method. The granulated silica method is one version of the powder-in-tube technique and potentially gives one a high degree of freedom regarding the applicable dopants, the maximum possible dopant concentration, the homogeneity of the dopants and hence the minimum refractive index contrast. Furthermore by using the granulated silica method, the geometry can be virtually adapted to any shape.

Recently, we have overcome the main limitation of this method – the background (scattering, propagation) losses - by using a sol-gel approach to produce granulate for the granulated silica method. So far, we succeeded in producing Yb/Al/P doped fibers with low propagation losses of 0.02dB/m at 1550nm and with an homogeneity down to the nano-scale level. Now, we have turned our attention to the production of fibers based on the sol-gel approach doped with multiple rare earths, Bismuth and Aluminium (Er/Nd/Bi/Al) in order to realize fibers with a broadband emission in the near infrared. We have previously succeeded in producing such doped Er/Nd/Bi/Al fibers with a broadband near infrared emission by the regular (non-sol-gel; oxides based) granulated silica method, however, these fibers suffered from high background losses, which we can now overcome by using the sol-gel approach.

In this paper, we present first results of an Er/Nd/Bi/Al doped fiber based on the sol-gel approach.

10232-23, Session 5

Comparative investigation of methods to determine the group velocity dispersion of an endlessly single-mode photonic crystal fiber

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Endlessly single-mode fibers, which enable single mode guidance over a wide spectral range, are indispensable in the field of fiber technology. A two-dimensional photonic crystal with a silica central core and a micrometer-spaced hexagonal array of air holes is an established method to achieve endless single-mode guidance. There are two possible ways to determine the dispersion: measurement and calculation.

We calculate the group velocity dispersion GVD based on the measurement of the fiber structure parameters, the hole diameter and the pitch of a presumed homogeneous hexagonal array and compare the calculation with two methods to measure the wavelength-dependent time delay. We measure the time delay on a three hundred meter test fiber with a homemade supercontinuum light source, a set of bandpass filters and a fast detector and compare the results with a white light interferometric setup. To measure the dispersion of optical fibers with high accuracy, a time-domain white-light interferometer based on a Mach-Zehnder interferometer is used. The experimental setup allows the determination of the wavelength dependent differential group delay of light travelling through a thirty centimeter piece of test fiber in the wavelength range from VIS to NIR. The determination of the GVD using different methods enables the evaluation of the individual methods for characterizing the endlessly single-mode fiber.

10232-24, Session 5

Unique method to determine the differential mode delay of specialty multimode fibers

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We developed an experimental setup for the determination of the differential mode delay (DMD) in fibers. This unique method of measurement is the basis for the characterization of specialty fibers including properties such as the chromatic dispersion, the fiber geometry and the DMD. These fibers have their application in the near-infrared and mid-infrared regime. Examples of uses of such fibers are supercontinuum light sources and high power lasers. Different modifications of these multimode fibers are applicable in extreme environments or for standard beam delivery over long distances. The exact knowledge of parameters such as the DMD is necessary to generate light sources with ether high energy, high intensity or high power or to analyze transmitted information when the fiber is used in a configuration for communication.

For the most exact measurement of DMD, we investigated a new type of method. It is capable of measuring the modal dispersion in two different ways. The first way is the standard transversal measurement, where the launching condition is altered by moving the radial position of the injected pulse while maintaining a zero-angle launching condition. The second way involves changing the launching angle into the fiber. This is done to get the most precise value for the DMD. Also, using a supercontinuum light source for the injection pulse, it is possible to vary the wavelength to be able to measure near the zero dispersion wavelength in order to investigate the effects of the chromatic dispersion.

10232-25, Session 5

Toward investigation of Brillouin scattering in multimode polymer and silica optical fibers

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Owing to substantial progresses in fiber optic communication the commercial establishment of fiber optic sensing has in the meantime become a reality. Especially, fiber optic distributed monitoring systems based on nonlinear scattering phenomena in optical fibers have been successfully implemented in the areas of both pipeline leak detection, geohazard effects and ground movement detection. The most important nonlinear scattering effect in optical fibers used for simultaneous temperature and strain sensing is called Brillouin scattering. The field-proven Brillouin sensing technique is capable of performing distributed monitoring over long distances within tens of kilometers. Thereby, the single-mode silica glass optical fibers are used by default as distributed fiber optic sensors. A supplemental sensory implementation of multimode optical fibers would entail new application fields for distributed Brillouin sensing. The greatest innovative potential can here be attributed to the use of the polymer optical fibers. Due to their material's characteristics as robustness under bending and stretching, distributed high strain Brillouin measurements are realizable in the future.

The first step to using the multimode fibers is adapting the measuring systems themselves to the new geometric and light propagation properties of this kind of the fibers. In this paper, we present a study aimed at characterizing the optimal fiber optic components for Brillouin sensing in multimode fibers. For this purpose the use of single-mode and multimode circulators as well as couplers typically used in the Brillouin measurement setups was investigated. On the one hand the undesired coupling losses between conventional fiber optic measurement system components and a multimode sensor fiber can be overcome by replacing the single-mode components with their own multimode equivalents. On the other hand the use of multimode fiber optic circulators and multimode couplers affects the mode distribution of laser light which can impair the measurement signal backscattered in the multimode sensor fibers. In view of an increasing interest in high strain measurements using polymer optical fibers as Brillouin-distributed sensors the investigation on Brillouin scattering effects in multimode fibers was performed on a low-attenuation perfluorinated graded-index polymer optical fiber. The obtained results were compared with those of a standard graded-index multimode silica glass optical fiber.

This study confirms the relevance of the adaptation of the measurement system components to the use of the multimode sensor fibers. In addition, due to mode coupling effects occurring in the tested polymer optical fiber itself the results show differences in the yield of the components adaptation in the sensory implementation of the two kinds of the tested optical fibers.

Monday - Thursday 24–27 April 2017

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10233-1, Session 1

Analysis of higher order harmonics with holographic reflection gratings

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Silver halide emulsions have been considered one of the most energetic sensitive materials for holographic applications. Nonlinear recording effects on holographic reflection gratings recorded on silver halide emulsions have been studied by different authors obtaining excellent experimental results. In this communication specifically we focused our investigation on the effects of refractive index modulation, obtaining high levels of overmodulation that will produce high order harmonics. We studied the influence of the overmodulation and its effects on the transmission spectra for a wide exposure range by use of 9 ?m thickness films of ultrafine grain emulsion BB640, developed with AAC developer and R-10 rehalogenating bleacher, using a red He-Ne laser (wavelength 632.8 nm) with Denisyuk configuration obtaining a spatial frequency of 4990 l/mm recorded on the emulsion. The experimental results show that high overmodulation levels of refractive index produce second order harmonics with high diffraction efficiency (higher than 75%) and a narrow grating bandwidth (12.5 nm). Results also show that overmodulation produce transmission spectra deformation of the second order harmonic, transforming the spectrum from sinusoidal to approximation of square shape due to very high overmodulation. Increasing the levels of overmodulation of refractive index, we have obtained higher order harmonics, obtaining third order harmonic with diffraction efficiency (up to 23%) and narrowing grating bandwidth (5 nm). This study allows obtaining a new easy technique to obtain narrow spectral filters based on the use of high index modulation reflection gratings.

10233-2, Session 1

Holographic recording in two-stage networks

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Holographic photopolymers create a permanent refractive index gradient in response to localized photo-initiated polymerization and the subsequent diffusion of mobile species in a rubbery polymer matrix. The resulting material is inherently low modulus, has low glass transition temperature and will readily uptake small molecules from the environment. To be environmentally robust, therefore, these polymers are typically packaged on one or both sides with a high modulus polymer or glass. The package adds weight and bulk, particularly to thin films, and the inherent delicacy of the polymer is a worrisome failure mode.

We demonstrate a potential solution to this problem by extending the traditional two-chemistry holographic photopolymer design. The solid matrix polymer is designed to have three distinct sets of material properties: 1) an initially liquid state appropriate for formulation and casting into the desired final shape, 2) a rubbery state with low glass transition temperature appropriate for holographic recording and 3) a final higher modulus state with improved mechanical robustness. We demonstrate several materials that follow this scheme.

The general chemical scheme is to form the second stage rubbery polymer network via a thiol Michael addition “click” reaction such that the matrix has a pendant stoichiometric excess of an orthogonal functional group. Holographic recording then takes place via the normal two-chemistry process. During final flood illumination of the material, the pendant functional groups are cross-linked to change the mechanical properties of the matrix. We demonstrate high (96%) efficiency holographic recording, low (1.1%) shrinkage, no oxygen sensitivity and recording into free-standing substrates.

10233-3, Session 1

Ultrarealistic imaging and OptoClones™ *(Invited Paper)*

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Recent improvements in solid state CW lasers, recording materials and light sources (such as LED lights) for displaying colour holograms are described. Full-colour analogue holograms can now be created with substantially better image characteristics than previously possible. To record ultra-realistic images depends on selecting the optimal recording RGB laser wavelengths. Analogue colour holograms of the Denisyuk type are the ones which really create the illusion of viewing a real object behind the plate rather than an image of it. It is necessary to use extremely low-light-scattering panchromatic recording materials, which means the use of ultra-fine-grain, silver-halide emulsions. The third factor is the light source used to display the recorded colour holograms. Progress in illumination technology, by employing the new LED lights, is leading to a further major reduction in display noise and to a significant increase of the clear image depth and brightness of the holograms. Recording and displaying colour holograms (referred to as OptoClonesTM) of museum artefacts are described.

10233-4, Session 1

Holographic optical elements as solar concentrators for space applications fabrication and thermal-optical characterization

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For space applications, normally, the solar concentrators use materials, mechanical structures and mirrors to reduce the area of photovoltaic cells(PV) that result more expensive. To better understand, about the 60% of complete economic budget allocated to the launch of a satellite is destined to acquire only photovoltaic cells. In this paper, we will evaluate, the possibility of reduce the cost of PV cells, using a planar solar holographic concentrators designed for space application, recorded on a new photosensitive material that result to be economic solution. The material was based on a sol-gel matrix formed by condensation of alkoxysilanes functionalized with organic pendant groups and they are characterized by interpenetrating organic and inorganic networks. We will evaluate the use of this new photosensitive material for realization of different kind of Holographic Optical Elements(HOE) that work as concentrators. In particular, we will see that an off-axis holographic cylindrical lens reunites a good property to focus, characteristic of a spherical holographic lens, together with a property to deflect the light at a designed angle, characteristic typically of a volume holographic grating(VHG)[1,2]. The set of this behavior reduce the PV cells area. To evaluate the behavior of our new photopolymer when exposed to extreme temperature changes, such as occurs in space environment, we will record, with green light, a VHG with a grating period of 1000 l/mm[3,4].We will effectuate a preliminary study of the diffraction

efficiency of VGH at room temperature(24°C), at 150°C for two hours and after its exposure to -80°C for 23 hours. The efficiency is evaluated as:

??=??1/(??0+??1), (1)

where P1 is the measured power of the 1st diffraction order and P0 is the measured power of the zero diffraction order. From this preliminary evaluation the efficiency does not vary significantly by varying the temperature of the material, making our photopolymer suitable for space.

After realization of spherical holographic lenses, with a Michelson interferometric set-up, and cylindrical lenses, with a Mach Zehnder interferometric set-up, we carried their optical characterization. In particular, for both types of holographic lens, we will evaluate the focal distance as a function of the incident wavelength, and their beams profiles in the focal points of lenses.

In conclusion, we will present the preliminary study, of the possibility that a new photosensitive material used as recording material for efficient holographic solar concentrators, could be used in space applications for solar concentrators.

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10233-5, Session 1

Double-blind digital inline holography from multiple near-field intensities

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In recent years coherent diffraction imaging and related techniques have gained in importance due to their ability to recover both modulus and phase information of complex-valued wave fields without the need for refractive or diffractive optical elements [1,2]. These methods have successfully been demonstrated for microscopic imaging of biological [3] as well as nanoscopic structures [4] and perform well even with partially coherent radiation sources [5]. However, standard phase retrieval schemes such as single-shot coherent diffraction imaging, ptychography, phase-shifting interferometry and holography require either a priori knowledge about the specimen or reference wave or rely on precise mechanical translation systems.

We present a phase retrieval technique for the recovery of complex-valued wave-fields from multiple near-field diffraction measurements. The proposed method does neither rely on any a priori knowledge about the sample nor on knowledge about an external reference wave, but instead uses multiple self-referencing object exit surface waves that are iteratively recovered. The key ingredient to our approach is a system of relaxed coupled waves that allow for the incorporation of holographic data. We use diffraction measurements of multiple exit surface waves as well as their holograms at multiple sample-detector distances to provide sufficient data redundancy to successfully reconstruct the complex-valued wave field. We demonstrate that this approach overcomes stagnation problems as encountered in other iterative schemes and perform a stability analysis. Parameters for robust performance are proposed. Numerical reconstruction is shown by simulation and experiment to be robust against systematic errors such as partial coherence effects, position uncertainty and various sources of noise. The method proposed is realizable at low cost with instrumentation available in typical optical laboratories.

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10233-6, Session 1

Improvement of spectral and axial resolutions in modified coded aperture correlation holography (COACH) imaging system

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Coded aperture correlation holography (COACH) is a recently developed incoherent digital holographic technique (Opt. Express 24, 12430, 2016). In COACH, two holograms are recorded: the object hologram for the object under study and another hologram for a point object called PSF hologram. The holograms are recorded by interfering two beams, both diffracted from the same object point, but only one of them passes through a random-like coded phase mask (CPM). The same CPM is used for recording the object as well as the PSF holograms. The image is reconstructed by correlating the object hologram with a processed version of the PSF hologram. The COACH holographic technique exhibits the same transverse and axial resolution of the regular imaging, but with the unique capability of storing 3D information. The basic COACH configuration consists of a single spatial light modulator (SLM) used for displaying the CPM. In this study, the basic COACH configuration has been advanced by employing two spatial light modulators (SLMs) in the setup. The refractive lens used in the basic COACH setup for collecting and collimating the light diffracted by the object is replaced by an SLM on which an equivalent diffractive lens is displayed. Unlike a refractive lens, the diffractive lens displayed on the first SLM, focuses light with different wavelengths to different axial planes which are separated by distances larger than the axial correlation lengths of the CPM for any visible wavelength. This characteristic extends the boundaries of COACH from three dimensional to four dimensional imaging with the wavelength as its fourth dimension. The four dimensional imaging capabilities of the modified COACH setup are demonstrated using two channels of illumination consisting two different wavelengths. In the first channel, a National Bureau of Standards (NBS) resolution chart is mounted and illuminated by an incoherent red light of central wavelength 635 nm, and in the second channel, a United States Air Force (USAF) resolution chart is mounted and illuminated by an incoherent green light of central wavelength 587 nm. Two PSF holograms are recorded for the two wavelengths using a point object mounted at the exact axial locations of the respective NBS and USAF objects. To validate the wavelength sensitivity of the modified COACH setup, the objects were mounted onto the same axial locations in the two channels and the two color object hologram was recorded. The different color objects can be reconstructed only by the corresponding PSF holograms of the same color even though the object holograms and the PSF holograms were recorded at the same axial locations. Therefore, the modified COACH setup can be used for four dimensional imaging with three spatial dimensions and the wavelength as the fourth dimension.

10233-7, Session 1

Quality inspection of security holograms considering the influence of diffraction gratings relief distortion

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Security holograms are widely used for authenticity protection of documents and products due to difficulties of such a protection mark falsification. The quality of holograms significantly depends on accordance of calculated and real phase relief parameters. We represent the method for automated quality inspection of security holograms. This method based on determining of phase relief parameters by registered results of the intensity distribution in diffraction orders. The profile of relief as a harmonious distribution is represented. Distortion of the ideal relief profile influence on the accuracy of this method. The mathematical expressions for evaluating the influence of the phase relief distortion on the intensity distribution in the diffraction orders are represented. Parameters of the correlation functions approximation describing the phase relief distortion are determined. The dependence of the intensity values from the standard deviation of the phase relief noise is represented. The results of quality inspection for real security holograms are shown.

10233-8, Session 2

Nanocomposite volume holographic gratings incorporated with ultrahigh refractive index hyperbranched polymer for diffractive optical elements *(Invited Paper)*

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Holographic dry photopolymers have received much attention owing to their light-manipulating capability in diffractive optics, optical data storage and optical communications. But simultaneously satisfying requirements for large refractive index modulation and dimensional stability are difficult to achieve in conventional photopolymers owing to their limited refractive-index range and inherent polymerization shrinkage. In this work we report on the characterization of volume holographic gratings recorded in a new type of photopolymerizable polymer nanocomposites incorporated with hyperbranched polymer (HBP) acting as transporting organic nanoparticles. It is intended for their use in diffractive optical elements. The HBP was prepared by the polycondensation of a diamine monomer with 2, 4, 6-trichloro-1, 3, 5-triazine in N, N-dimethylacetamide, followed by the end-capping reaction with aniline. The synthesized HBP exhibits ultrahigh index of refraction (> 1.8) since it possesses triazine and aromatic ring units. Its average size and heterogeneity are approximately 10 nm and 4.4, respectively. In order to obtain high dispersion of HBP in monomer, we mixed HBPs with solvents used for a plasticizer. This syrup was further mixed with a photoinitiator titanocene and multi-functional acrylate monomer to prepare photopolymerizable polymer nanocomposite films for holographic measurements. We used a two-beam interference setup to write an unslanted transmission volume grating at grating spacing of 1 ?m and at a wavelength of 532 nm. We show that a volume grating with the refractive index change larger than 0.02 can be recorded at HBP concentrations higher than 25 vol.%.

10233-9, Session 2

Holographic analysis of photopolymers

Amy C. Sullivan, Marvin D. Alim, David J. Glugla, Robert R. McLeod, Univ. of Colorado Boulder (United States)

Two-beam holographic exposure and subsequent monitoring of the time-dependent first-order Bragg diffraction is a common method for investigating the refractive index response of holographic photopolymers for a range of input writing conditions. The experimental set up is straightforward, and well-known coupled wave theory can be used to separate measurements of the change in index of refraction (?n) and the thickness of a transmission hologram. However, practical difficulties in experimental holographic systems, such as the finite size of Gaussian read and write beams, the imperfect visibility of the interference pattern, and shrinkage-induced non-uniformities in the photopolymers themselves affect the diffraction efficiency of the holograms and make it difficult to obtain accurate information about the material. These effects become pronounced as the hologram efficiency approaches 100% and are critical for over-modulated exposures.

We present a careful study of the effects of experimental system parameters on the transmission Bragg holography analysis of photopolymer materials. These calculations reveal how non-ideal recording and readout conditions result in errors in the extracted material performance and provide a method to correct for these errors. We also show how the shape of the Bragg angular selectivity curve can provide insight into the behavior of the material. Finally, we demonstrate fitting of very high ?n transmission holograms. These measurements are compared to growth of reflection holograms in the same material, measured via real-time UV-VIS spectroscopy.

We use this analysis to study a model high ?n two-stage photopolymer holographic material. A lower index of refraction, rubbery polyurethane network is used to set up the scaffolding through which the higher index of refraction acrylate monomers diffuse. We perform a systematic study of the diffraction efficiency, along with the angular and wavelength selectivity of high index of refraction acrylate writing monomers in order to gain insight into the design of materials for high diffraction efficiency, high fidelity transmission and reflection holographic elements.

10233-10, Session 2

Shrinkage measurament for holographic recording materials

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There is an increasing demand for new holographic recording materials. One of them are photopolymers, which are becoming a classic media in this field. Their versatility is well known and new possibilities were created by including new components, such as nanoparticles or dispersed liquid crystal molecules in classical formulations, making them interesting for additional applications in which the thin film preparation and the structural modification have a fundamental importance. Prior to obtaining a wide commercialization of displays based on photopolymers, one of the key aspects is to achieve a complete characterization of them. In this sense, one of the main parameters to estimate and control is the shrinkage of these materials. The volume variations change the angular response of the hologram in two aspects, the angular selectivity and the maximum diffraction efficiency. One criteria for the recording material to be used in a holographic data storage application is the shrinkage, maximum of 0.5%. Along this work we compare two different methods to measure the holographic recording material shrinkage. The first one is measuring the angle of propagation for both diffracted orders ±1 when slanted gratings are recorded, so that an accurate value of the grating vector can be calculated. The second one is based on interference measurements at zero spatial frequency limit. We calculate the shrinkage for three different photopolymers: a polyvinyl alcohol acrylamide (PVA/AA) based photopolymer, one of the greenest photopolymers whose patent belongs to the Alicante University called Biophotopol and on the last place a holographic-dispersed liquid crystal photopolymer (H-PDLC).

10233-11, Session 2

Thermal effects of the functionalities of chain transfer agent on photopolymer holographic volume gratings

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The photopolymerizable nanoparticle-polymer composites (NPCs) have thus far shown their excellent performance in practical applications, such as holographic data storage, nonlinear optics and neutron optics. We have demonstrated two-fold enhancement of the saturated refractive index modulation (?nsat) of ZrO2 NPC volume gratings recorded at high spatial frequencies by doping with a single functional thiol as a chain transfer agent (CTA). This result suggested that the incorporation of a CTA in an NPC is very useful for holographic applications of volume gratings in light and neutron optics. Such chemical modification of NPC volume gratings may be more effective by doping with multifunctional thiols. This is so because polymer features such as the molecular weight and the crosslinking network density can be tailored more diversely by introducing multifunctional thiols in photopolymers. The influences of varying functionalities of thiols as chain transfer agents on the thermal stability of a volume grating recorded in a photopolymerizable ZrO2 nanoparticle-polymer composite film have been investigated.

10233-12, Session 2

Holographic properties of new chloride photo-thermo-refractive glasses

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In this research we present new holographic material based on fluoride photo-thermo-refractive glass(PTR) - chloride PTR glass. One of the benefit of this type of PTR glass is positive refractive index change, which can be utilized for waveguide creation in combination with Bragg gratings in single volume of the material. Initial study showed that this kind of glass has difference in refractive index between virgin and UV exposed and thermal treated regions. During this work, for the first time volume Bragg gratings were recorded in this kind of material. The first experiments revealed that such gratings are mixed i.e. possess both absorption and phase components. Complex analysis shows that both refractive index and absorption coefficient are modulated inside the grating structure. During this work, we had to optimize a thermal treatment process to maximize the effect of refractive index change. Also we investigated photosensitivity of the material. We found out that at first there is no strict dependence of the refractive index change from dosage, but as we continue the process of thermal treatment – dependence is appear. Exposure influence on the refractive index change for this glass differs from fluoride one and shows some sort of saturation after the exposure of 4-6 J/cm2. We distinguished refractive index change and absorption coefficient change and observed both behavior with increasing thermal treatment time. We found out that the increase of thermal treatment time results in the significant refractive index change. At the same time the absorption does 'not practically change. It was found that maximum modulation of refractive index is comparable with fluoride PTR glass and achieves value of 900 ppm. The modulation of absorption is equal to induced absorption caused by silver nanoparticles and depends from reading wavelength. Our study shows that almost all absorption is modulated inside the grating.

10233-13, Session 2

Development of holographic media based on organic carbazole polymers

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Development of photothermoplastic carriers based on organic photosensitive semiconductors for optical information recording is an actual problem. Photothermoplastic carriers based on carbazole-containing polymers exhibit high values of photosensitivity in the visible spectral range, reversible optical data registration process and does not pose a risk of environmental pollution [1-3].

The main objective of this research was to develop a new carbazole-containing copolymers showing high values of photosensitivity for creating of reversible photothermoplastic carriers for registration of the holographic information in real time. Carbazole-based copolymers have been synthesized from N-carbazolyl methyl methacrylate (CMM) [4]. Monomer CMM was obtained from carbazole, paraformaldehyde and acryloyl chloride. The synthesis of copolymers was carried out by a radical mechanism and a structural fragment is represented by the formula: [SPIE note: FORMULA CONTAINS SPECIAL CHARACTERS NOT AVAILABLE HERE]

Were synthesized copolymers CMM : OMA containing CMM units from 50 to 80 mol%. Based on CMM : OMA copolymers were obtained photosensitive layers sensitized with 2,4,7 - trinitrofluorenone. The obtained photosensitive layers in the thickness range 1,5 - 2,5 ?m were deposited on a flexible transparent substrate precoated with a semitransparent conducting electrode. Thus obtained photothermoplastic media were investigated for recording holographic images in the laser emission 532 nm. On the received media were registered holographic grating in real time (up to 3 s) with a diffraction efficiency of 10% and a resolution of up to 2000 mm-1.

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10233-14, Session 3

Performance optimization in mass production of volume holographic optical elements (vHOEs) using Bayfol® HX photopolymer film *(Invited Paper)*

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Volume Holographic Optical Elements (vHOEs) gained wide attention as optical combiners for the use in smart glasses and augmented reality (SG and AR, respectively) consumer electronics and automotive head-up display applications. The unique characteristics of these diffractive grating structures – being lightweight, thin and flat – make them perfectly suitable for use in integrated optical components like spectacle lenses and car windshields. While being transparent in off-Bragg condition, they provide full color capability and adjustable diffraction efficiency. The instant developing photopolymer film Bayfol® HX provides an ideal technology platform to optimize the performance of vHOEs in a wide range of applications.

Important for any commercialization are simple and robust mass manufacturing schemes. In this paper, we present an efficient and easy to control one-beam recording scheme to copy a so-called master vHOE in a step-and-repeat process. In this contact-copy scheme, Bayfol® HX film is laminated to a master stack before being exposed by a scanning laser line. Subsequently, the film is delaminated in a controlled fashion

and bleached. We explain working principles of the one-beam copy concept, discuss the opto-mechanical construction and outline the downstream process of the installed vHOE replication line. Moreover, we focus on aspects like performance optimization of the copy vHOE, the bleaching process and the suitable choice of protective cover film in the re-lamination step, preparing the integration of the vHOE into the final device.

10233-16, Session 3

Analysis of holographic photopolymers for integrated optical systems via quantitative phase microscopy

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Optically-driven diffusion of high refractive index molecules within a transparent thermoset polymer matrix is a promising platform for hybrid optics which combine a wide range of optical structures from large scale holograms to lenses to gradient index waveguides in a single integrated optical system. Design of such a system requires characterization of the optical response of the material at a wide range of spatial scales, from 100s of nanometers for reflection holograms, to millimeters for larger optical elements. The optical response must also be probed over a wide range of intensities, from mW/cm2 for large area exposures by low power, continuous wave lasers for holography to GW/cm2 for focused exposures from high power, pulsed lasers for two-photon direct write of isolated waveguides.

While holographic analysis of the photopolymers is appropriate to probe the smaller spatial scales and lower intensity optical response, quantitative phase mapping of isolated structures is needed to probe the response to the higher intensities of focused pulsed lasers used to write waveguides. Popular techniques such as Shack-Hartman wavefront sensing and interferometry either lack the resolution necessary to study isolated micron-scale structures or are sensitive to phase aberrations within the optical system. The transport of intensity equation (TIE) derived by Teague in 1983, is a non-interferometric imaging technique that directly recovers the optical phase delay by using the axial change in intensity of a series of defocused images about the object plane. Additionally, the TIE does not suffer from strict coherence requirements of the illumination source and may be implemented in a simple brightfield microscope. Given the thickness and shape of the phase structure, the TIE can be used to directly map the refractive index contrast of a 2D or 3D phase element.

We apply the TIE to demonstrate quantitative index measurements of 10 ?m scale localized gradient index structures written into diffusive photopolymer materials using both single- and two-photon polymerization. These quantitative measurements allow us to study the effect of different exposure conditions and material parameters such as writing beam power, exposure time, and wt% loading of the writing monomer on the overall profile of the refractive index structure. We use our measurements to probe the time scales over which diffusion is significant, and take advantage of the diffusion of monomer with a multiple write system that achieves a peak refractive index contrast of 0.03. These phase microscopy measurements, along with holographic analysis of these materials, allows us to design optical systems including both large-scale holograms along with localized structures such as waveguides.

10233-17, Session 3

Optimisation and coupling of high-performance photocyclic initiating systems for efficient holographic materials

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For fabrication of diffractive optical elements or for holographic data storage, photopolymer materials have turned out to be serious candidates, taking into account their performances such as high spatial resolution, dry processing capability, ease of use, high versatility. From the chemical point of view, several organic materials are able to exhibit refractive index changes resulting from polymerization, crosslinking or depolymerization, such as mixtures of monomers with several reactive functions and oligomers, associated to additives, fillers and to a photoinitiating system (PIS).

The most versatile process is the free radical photopolymerization which offers the most important choice of materials and potential PIS. The efficiency of the PIS is determined by the absorption properties, the quantum yield of initiating radicals and the reactivity of these radicals towards the monomer. It is well recognized that the PIS is the corner stone of photopolymerization process. Holography also represents an interesting and growing field due to an increasing demand in security or data storage. The development of applications in holography is directly governed by the photosensitivity of the photopolymer and the diffraction efficiency which could be obtained. Therefore, there is a need for highly efficient photoinitiating systems capable to initiate the photopolymerization reaction at relatively low dose.

In this work, the efficiencies of two and three component PIS as holographic recording materials are analyzed in term of photopolymerization kinetics and diffraction yield. The selected systems are based on visible dyes, electron donor (e.g. amines) and electron acceptor (e.g iodonium salts) as the third component. In order to investigate the influence of the photophysical properties of dye on the holographic recording material performance time resolved and steady state spectroscopic studies of the PIS are presented (i.e. nanosecond. laser flash photolysis). This detailed photochemical studies of the PIS outline the possible existence of photocyclic initiating systems (PCIS) where the dye is regenerated during the chemical process (see figure). Simultaneously, these visible curable systems are associated to fluorinated acrylate monomers for the recording of transmission gratings. In order to get more insight into the hologram formation, gratings' recording curves were compared to those of monomer to polymer conversion obtained by real time Fourier transform infrared spectroscopy (RTFTIR). This work outlines the importance of the coupling of the PIS (i.e. the photochemical reactions) and the holographic resin. It is demonstrated by RT-FTIR that the photocyclic behavior have a great positive impact on the photopolymerization efficiency. Moreover the application of the two PCIS in holographic recording outlines the importance of the photochemistry on final holographic material properties: here a sensitive material with high diffraction yield is described. Indeed, this work outlines the importance of the coupling between the photochemistry underlying the radicals photogeneration and the holographic resin.

10233-18, Session 3

Synthetic holograms based on photochromic diarylethenes

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We report on our research activity to design and produce synthetic holograms (Computer Generated Holograms - CGHs) for wavefront shaping and optical testing of complex surfaces with photochromic materials belonging to the class of diarylethenes.

Diarylethenes are P-type photochromic systems showing reversible light-induced modulation of optical properties, e.g., transmittance and refractive index, in the visible and near infrared regions. Opaque after exposure to ultraviolet light, these materials become transparent when illuminated with visible light. Transmittance can be progressively tuned according to the illumination dose, and the pattern written and erased several times with light. At dark, the pattern is stable at room temperature for years.

We demonstrated binary Computer Generated Holograms based on of photochromic polymers, to be used as adaptable reference surfaces in interferometric tests. We encoded by Direct Laser Writing binary amplitude Fresnel Zone Plates into photochromic substrates and tested them into an interferometric setup. The contrast between transparent and opaque zones was high enough to obtain very clear interference fringes and diffraction efficiencies very close to the theoretical value.

More recently, we exploited the non-threshold behavior of photochromic polymers to encode grayscale CGHs, which give a better wavefront reconstruction than binary holograms. We propose to use a device based on a Digital Micro-mirror Device, developed at LAM (Laboratoire d'Astrophysique de Marseille), as a real-time reconfigurable mask for writing grayscale CGHs on the photochromic plates. We have been able to successfully record the very first amplitude grayscale CGH, with a contrast greater than 50, and reconstruct it with high fidelity in shape, intensity and size.

We are also investigating multistate photochromic systems. By properly mixing diarylethenes with different absorption properties, two or more holographic patterns can be individually encoded on the same substrate and reconstructed at two or more wavelengths. Photochromic materials make wavelength multiplexing possible, to be exploited with multi-lambda interferometry, for example in the testing of complex and segmented optics.

10233-40, Session 3

Light amplification by photorefractive ferroelectric liquid crystal blends containing quarter-thiophene photoconductive chiral dopant *(Invited Paper)*

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The photorefractive effect is a phenomenon that forms a rewritable hologram in a material. The most characteristic phenomenon of the photorefractive effect is the asymmetric energy exchange, in which the energy of one of the interfering laser beams transfer to the other. This phenomenon can be utilized in devices including 3D displays, optical tomography, novelty filters, phase conjugate wave generators, and optical amplification. Ferroelectric liquid crystal blends composed of a smectic liquid crystalline mixture, a photoconductive chiral dopant, and an electron trap reagent exhibit significant photorefractivity together with rapid responses. As such, they allow the dynamic amplification of moving optical signals. The ferroelectric liquid crystals used for practical application are mixtures of several liquid crystalline compounds and chiral dopants. In order to obtain a photorefractive FLC, a photoconductive compound is also added to the FLC mixture. However, in the most case, the photoconductive compounds are not liquid crystalline materials, addition of the photoconductive compound to the FLC mixture disturbs the alignment of FLC molecules. Thus the light scattering in the FLC medium increases. In order to avoid this problem, photoconductive compounds that also possess chiral structure were synthesized. One can obtain a photorefractive FLC just by mixing of the photoconductive chiral compound with a FLC mixture. We have reported that photorefractive FLC blends containing photoconductive chiral dopants exhibits a large photorefractivity and a fast response. The photoconductive chiral dopants used in the previous study were terthiophene compounds. The absorption of terthiophene is shorter than 500 nm so that 488 nm lasers were used to induce the photorefractive effect. In the present study, quarter-thiophenes were synthesized and mixed with a smectic liquid crystal to form a ferroelectric liquid crystals. The photorefractive properties in longer wavelength regions were investigated.

10233-19, Session 4

New photosensitive systems for volume phase holography *(Invited Paper)*

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Volume phase holograms and holographic optical elements are of large interest thanks to the high efficiency and good S/N. For these reasons, they found for example application as dispersing elements in astronomical spectrograph, Raman systems. Volume phase holograms work thanks to a periodic modulation of the refractive index in a layer of a suitable photosensitive material with a constant thickness.

The photosensitive material play a key role in determining the performances of the holographic element. Different classes of holographic materials are known; in particular dichromated gelatins (DCGs), silver halides, photopolymers, photochromic materials. All of them show some advantages, such as the large refractive modulation in DCGs, the self-developing and high sensitivity of photopolymers and rewritability of photochromic materials. In spite of the availability of all these materials, it is interesting to study new chemical systems that are photosensitive and provide a modulation of the refractive index.

We studied polymeric systems that undergo the photo-Fries reaction upon UV light exposure. We perform a theoretical study of such systems and we measured the change in the refractive index as function of the UV light dose. We then highlighted the mechanism that induces the modulation of the refractive index, which is mainly based on a change in the material density. Other molecules that undergo to this reaction have been recently synthesized. Such molecules show an absorption spectrum going from from the UVB to the UVA depending on the chemical structure. The refractive index modulation has been measured in polymer matrix as function of the content of photosensitive moiety and UV dose.

Another interesting system that has been studied is the diazo Meldrum's acid (DMA), which is knows in the field of deep UV photolithography as sensitizer. Here, a change in the refractive index occurs, which is due to the loss of nitrogen molecule upon photoreaction. Such modulation has been measured in CAB (cellulose acetate butyrate) matrix as function of the content of DMA and the illumination conditions.

All of these studied systems provided interesting hints for the developing of a new class of self-developing holographic materials.

10233-20, Session 4

Novel gratings for next-generation instruments of astronomical observations

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We would introduce development of the birefringence volume phase holographic (VPH) grating, the volume binary (VB) grating, the hybrid grism and the reflector facet transmission grating. Test fabrication of birefringence VPH gratings with liquid crystals of UV curable are performed. We successfully fabricated die of silicon for the VB grating with high aspect grooves. The die of surface relief gratings of hybrid grism for MOIRCS of the Subaru Telescope with acute angle grooves on to a work of Ni-P alloy of non-electrolysic plating was fabricated by using an ultra-precision machine and diamond bite.

10233-21, Session 4

Predictive modeling of two-component holographic photopolymers

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Photopolymers are the dominant recording medium for Bragg holography in commercial applications due to their low cost in large area and self-developing characteristics. Single chemistry polymers, in which the same photopolymerization chemistry is used both to form the solid host and record patterned features, have been extensively studied by Sheriden et. al. However, recent commercial development has focused on two-

component polymers in which a thermoset matrix largely determines the mechanical properties and the recording is performed with a chemically orthogonal mobile photopolymer.

To understand and optimize these two-component materials, a general strategy for characterizing the reaction/diffusion kinetics of photopolymer media is proposed, in which key processes are decoupled and independently measured. This strategy enables prediction of the maximum expected refractive index response, solely on the basis of the formulated chemical components. The degree to which a material does not reach this "formula limit" reveals the fraction of monomer that has participated in unwanted reactions. We show that these reactions not only rob the material of index contrast, they also reduce spatial resolution, increase shrinkage and potentially impact the material lifetime. This approach is demonstrated for a model material similar to commercial media, achieving accurate predictions of refractive index response over three orders of exposure dose (~1 to ~1000 mJ /cm2) and feature size (0.35 to 500 ?m) for both the first and second harmonic.

We apply this model to a family of urethane/acrylate two-chemistry photopolymers to illustrate its utility. To understand the applicability of the fundamental conclusions of the model beyond just these chemistries, we also survey the literature of holographic photo-polymers. Specifically, we analyze material design strategies via quantitative analysis of the recording fidelity, maximum refractive index change and the degree to which they achieve this limit. The survey shows that, despite the wide range of chemical strategies, the limits to holographic material performance can be understood in a common design framework. Finally, this analysis is extended to estimate achievable future performance improvements.

10233-22, Session 4

Mechanical response of holographic photopolymers

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Two-chemistry photopolymer systems are attractive platforms for a wide range of optical and mechanical applications due to the orthogonal chemistries of the initial thermoset matrix and the subsequent photo-initiated polymerization. This scheme allows the mechanical and optical properties of the materials to be individually addressed. However, in many systems, the mechanical properties of both the initial matrix and the photopolymer system affect the performance of these materials in all applications from holography to optically-actuated folding.

We present a mechanical model along with experimental demonstrations of a two-chemistry holographic photopolymer system. The mechanical behavior is modeled using mixture theory considering solid-like and fluid-like components. The mechanical response is governed by the competition between transport of free monomers by diffusion and rate of polymerization induced by light. A 3D finite element model is used to simulate the mechanical and chemical responses in time. The model uses standard material measurements to predict both large-scale deformation such as bending and more localized stress and strain.

To validate the model, we demonstrate bending of thin strips in this two-chemistry photopolymer system with UV light activation. An optical absorber is added to create an intensity profile that decreases in depth. The UV light initiates photopolymerization in the bright areas, causing an initial shrinkage and bending of the film toward the light. The monomer concentration gradient results in diffusion of monomer from the dark areas to the bright areas, causing swelling. The swelling results in bending of the film away from the light, in good agreement with the model. We achieve bending of 120 ?m thick films, with radii of curvature as small as 1 mm in less than 2 hours with a single optical exposure and no post processing. In addition to this large scale bending, we demonstrate that the model can be used to predict surface deformations that can be used for surface relief optical elements.

Mechanical deformations during material processing affect the performance of all applications of holographic photopolymers. The mechanical model allows us to understand how shrinkage and swelling properties of a particular material system affect the performance of that system over a wide range of illumination conditions. This will allow for better design of materials and optical exposures to control the final optical and mechanical properties of devices such as holographic optical elements.

10233-23, Session 4

Effect of rare-earth-dopants on Bragg gratings recording in PTR glasses

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Feature of the photo-thermo-refractive glass (PTR) glass is an ability of doping the glass with rare earth (RE) ions and volume Bragg gratings recording, i.e. such material can play a role of laser and holographic medium simultaneously. In present paper, we represent a study on the effect of RE dopants (lanthanum, erbium, ytterbium, and neodymium) on the process of the photo-thermo-induced (PTI) crystallization. During this work, we investigated each step of the PTI crystallization process including (i) silver particle formation, growth of (ii) shell and (iii) nanocrystal. To perform these observations, we reduced the temperature of thermal treatment below the glass transition temperature to slow down all processes inside the glass. We found out that the silver nanoparticles formation process does not depend from the concentration of RE ions and is the same as in case of the parent PTR glass. In other hand the growth kinetics of AgBr-NaBr shell and NaF nanocrystals differ from the parent glass and depend on RE concentration. Our observations show no difference in final position of plasmon resonance, which means that the PTI crystallization process itself stays the same and is not affected by the RE dopants. Further study shows that utmost achievable refractive index change falls off with rare earth dopant concentration increase mainly due to the bond formed between dopant and fluorine. This bond prevents fluorine from participation in crystallization process thus overall volume fraction of the crystalline phase decreases. This effect can be corrected by addition of fluorine in the chemical composition of the glass at the synthesis. In conclusion, we show that refractive index change in doped glass with appropriate concentration of additional fluorine is same as in the parent glass (1500 ppm). Thus, the possibility of fabrication of distributed feedback lasers based on doped PTR glass was discussed.

10233-24, Session 5

Holographic 3D imaging through diffuse media by compressive sampling of the mutual intensity *(Invited Paper)*

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In the past decades there has been a growing interest in 3D imaging through scattering or turbid media. Related techniques have great applications in industrial inspection, astronomy, medical healthcare and biology [1].

In this publication we present a method that provides 3D imaging through diffuse media without the requirement of a specific reference wave. It is based on sampling of the mutual intensity function behind the scattering medium in order to recover a three dimensional representation of the scene in front of it. The sensor is a lateral shear interferometer that detects the mutual intensity of the imaged scene behind the scattering medium. Coherence gating is accomplished by illuminating the scene with partially coherent light that exhibits low temporal coherence but good spatial coherence, such as provided by a light emitting diode (LED) for example. Due to the low coherence, only ballistic photons will preserve sufficient spatial coherence and hence contribute to the measured mutual intensity, while the scattered light appears as incoherent background illumination.

The mutual intensity across the object plane is a four dimensional function. However, in case of a circular symmetric light source and the object in focus it becomes sparse and we can assign a two dimensional complex amplitude to it in order to fully describe it. In this situation it is sufficient to apply the compressive sampling scheme of computational shear interferometry (CoSI) [2] in order to sample a very small sub space of the mutual intensity and yet fully recover it. The assigned complex amplitude shows all properties of a phase shifted hologram of the scene under investigation, providing three dimensional imaging, numerical refocusing and quantitative phase contrast imaging capabilities.

In contrast to existing interferometric methods such as low coherence interferometry (LCI) [3], coherence holography [4] or photon-correlation holography (PCH) [5], the presented technique does not require adjustment or guidance of a reference wave. This advantage greatly enhances the flexibility of the system and enables applications towards remote sensing as well as investigation of moving objects. Furthermore, due to the common path nature of the sensor, the method is insensitive against mechanical distortions and therefore does not need any mechanical stabilization.

To demonstrate the method, we show experimental results from the field of quantitative phase contrast imaging that has strong applications in cell biology and medical healthcare. We also proof volumetric imaging and numerical refocusing of objects in order to emphasize the holographic capabilities of the technique.

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10233-25, Session 5

Speckle noise reduction in single-shot holographic two-wavelength contouring

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Form measurements of technical objects play an important role for quality inspection in manufacturing processes [1]. If the investigated surface is optically rough, a two-wavelength contouring approach is employed, where two measurements associated with two different wavelengths have to be measured. However, this technique has a major problem with the measurement accuracy since speckle fields corresponding to different wavelengths are not fully correlated. Consequently, the result is corrupted by decorrelation noise which depends on the wavelength difference [2].

Recently we proposed a method to reduce speckle decorrelation noise [3] based on averaging the results obtained from multiple measurements with the varying direction of illumination. For different illumination directions with the same angle of incidence, different free-space speckle fields generated by the object will travel towards the recording plane. If the illumination point is shifted by more than the aperture‘s diameter of the observation, the corresponding speckle pattern will be fully decorrelated. The corresponding noise terms of the phase difference have zero mean and the sum of them will become real-valued as more summands are added. Hence, the influence of the decorrelation noise on the phase will be considerably reduced. In contrast to the state the art, averaging the whole complex amplitude of the wave field in the observation plane is utilized rather than utilizing only the phase distribution. However, the measurements process is time-consuming, since the illumination angle was varied mechanically and the two patterns corresponding to the two wavelengths had to be recorded consecutively.

Here we present an experimental configuration that enables real-time form measurements from a single-shot camera exposure. It combines two-wavelength contouring approach [4] and spatial multiplexing synthetic-aperture Digital Holography [5]. The synthetic-aperture in this work is formed by simultaneously illuminating the test object from two different angles. The two illumination directions and the two-wavelength contouring result in four holograms which are spatially multiplexed on a single camera shot avoiding unwanted cross-interference between them. We refer to this principle as coherence-gating. Thus the advantages offered by both real-time contouring and spatial holograms multiplexing are combined. In contrast to standard holographic contouring methods, the proposed technique reduces speckle decorrelation noise and enables real-time form measurement. Using this technique, the shape of a micro cold drawing part is determined.

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10233-26, Session 5

Reflective-type digital holographic microscopy using induced self-pumped phase conjugation technique

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Techniques of noise suppression from the perspective of reference arm has been maturely developed. The object counterpart, however, is still in its infancy. Self-pumped phase conjugation technique which involves a $BaTiO_3$ crystal was introduced unto reflective-type digital holographic microscopy to suppress scattering noise derived from the object arm, prior to recording stage. A phase distorter was introduced as scattering source, and signal-to-noise ratio was calculated. Furthermore, induced method was proposed to speed up the response time.

10233-27, Session 5

Sparse based terahertz reflective off-axis digital holography

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Terahertz radiation lies between the microwave and infrared regions in the electromagnetic spectrum. Emitted frequencies range from 0.1 to 10 THz with corresponding wavelengths ranging from 30 ?m to 3 mm. Terahertz radiation can be emitted over a wide spectral range but using a coherent Terahertz source allows illumination by a narrow spectral bandwidth. This kind of radiation has a high penetration depth which makes it useful for security applications and non-destructive testing. The range of radiation involved is highly absorbed by water. Coupled with a deep penetration

depth this has many uses in medical imaging and diagnostics. In this paper, a continuous-wave Terahertz off-axis digital holographic system is described. The Terahertz source is a far-infrared emitting Carbon Di-Oxide (CO2) pumped laser system. An output power of 60 mW and frequency of 2.52 THz (wavelength is 118.83 mm) is achieved. Collimation and beam expansion of the system using Gold-coated parabolic mirrors is described. The off-axis hologram of the sample is then captured using a pyroelectric detector with a resolution of 320 x 320 pixels. Each pixel size has an area of 80 μm x 80 μm with an active area of 75 μm x 75 μm. For this paper, we capture a digital hologram of a metal coin. A Gaussian fitting method and image normalisation techniques are employed on the recorded hologram dataset. A synthesised contrast enhanced hologram is digitally constructed. Numerical reconstruction is achieved using the angular spectrum method of the filtered off-axis hologram. This removes both the DC and twin images and results in both amplitude and phase images of the sample under observation. Numerical autofocusing algorithms can be applied to estimate the correct reconstruction distance of the hologram. This provides an automated and efficient evaluation method to obtain an optimized value required for numerical propagation. A comparison of sparse compression technique for the terahertz digital hologram dataset captured by this off-axis digital holographic system is also presented.

10233-28, Session 5

Terahertz inline digital holographic multiplane imaging method

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Terahertz waves of which frequency spans from 0.1 to 10 THz bridge the gap between the infrared spectrum and microwaves. Owing to the special features of terahertz wave, such as penetrability and non-ionizing, terahertz imaging technique is a very significant and important method for inspections and detections. Digital holography can reconstruct the absorption and phase distributions of a sample without scanning and it already has many successful applications in the visible and infrared light area. The terahertz in-line digital holographic multi-plane imaging system which is presented in this paper is the combination of a continuous-wave terahertz source and the in-line scheme of digital holography. In order to observe a three dimensional (3D) complex shape sample only a portion of which appears in good focus, the autofocusing algorithm is brought to the system. The synthetic aperture method is applied to provide the high resolution imaging effect in the terahertz waveband. The terahertz in-line digital holographic multi-plane imaging system with a synthetic aperture method was built, and a two-dimensional electronic translation stage was added to the original configuration. The source was the terahertz quantum cascade laser (QCL), which was of our own manufacturing, where the wave numbers ranged from 101 to 104 cm?1. The intensity of the emitted terahertz wave had three peaks: 97?m, 97.6?m, and 98.9 ?m with a ratio of 4:1:2, respectively. The output operating power of terahertz QCL was set at 1 mW. To satisfy the imaging requirement of the in-line scheme, two terahertz convex lenses with the effective focal lengths of 13 mm were employed to collimate and expand the beam. The detector had 320 pixels ? 240 pixels and the pixel pitch was 23.5 ?m ? 23.5 ?m, thus the total size of the screen was 7.52 mm ? 5.64 mm. The captured frame rate of the detector was 8.5 Hz. After the data acquisition, the data analysis process is conducted. Both intrinsic twin images and defocused objective images confuse the quality of the complex value distribution in an individual reconstructed plane. In order to solve this issue, phase retrieval iteration algorithm is used for data processing. In addition, the reconstructed amplitude image in each plane multiplies the mask of which the threshold value depends on the results of the autofocusing curve. After accomplishing the restriction, the transparency of each slice is changed. Then all the slices are stacked to a final result by using a three dimensional visualization and analysis software tool called Avizo. A sample with simple artificial structure is observed which verifies that the present method is an authentic tool to acquire the multi-plane information of a target in terahertz waves. It can expect a wide application in terahertz defect detecting, terahertz medical inspection and other important areas in the future.

10233-29, Session 6

Analysis of data recorder optical scheme impact on quality of computer generated Fourier holograms in holographic memory system

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Application of computer generated Fourier holograms (CGFH) allows to simplify the process of holograms record in holographic memory system. Numerically synthesized Fourier hologram of information points is used to store the encoded binary information. To ensure that information can be recovered properly an optimal synthesis algorithm must be used. Also the analysis of recorder optical scheme impact on quality of recorded CGFH and definition of the optical recorder system requirements provides an information recovery with acceptable BER. This article is dedicated to a problem of correct construction of data recorder optical scheme.

10233-30, Session 6

Algorithms used for read-out optical system pointing to multiplexed computer generated 1D-Fourier holograms and decoding the encrypted information

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Computer synthesized 1D-Fourier transform holograms (1D-CGFH) are used for multiplex data record in projection type holographic memory data recorder. Pointing of read-out optical system to one-dimensional hologram for selective data recovery from multiplexed 1D-CGFHs plays significant role in the process. In this article several approaches to optical system pointing are considered, requirements are: high accuracy of data recovery with maximum speed. Also the algorithm for decoding the data page images restored from 1D-CGFH is presented. The quality of holographic memory system based on 1D-CGFH projection record is considered by means of BER.

10233-31, Session 6

Comparison of two methods for equalising the diffraction efficiency of different spatial frequency components of holographic optical elements

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Conventional optical elements are heavy and expensive and in many applications they could be replaced by the inexpensive, lightweight and flexible diffractive optical element. Holographic Optical Elements (HOE) are one type of diffractive optical elements, fabricated by recording the

pattern formed by at least two interfering beams of light. Holographic optical elements find many applications including, spectroscopy [1] , astronomy [1], ultrafast laser [1] and solar concentrators [2]. Diffraction efficiency is an important parameter which describes the efficiency with which diffractive optical elements redirect the light. For most practical applications, high diffraction efficiency is essential and should be constant across the whole aperture of the element.

In this work, off-axis holographic cylindrical focusing lenses have been fabricated using the two beams recording technique. Because of the variation in the angle at which the two beams meet, the spatial frequency at each point differs from another point across the element. In many photopolymer materials, the diffraction efficiency obtained at specific recording conditions varies with spatial frequency. This causes a variation in diffraction efficiency across the element. Since a uniform diffraction efficiency is important for HOE lens, this paper focuses on improving that uniformity. Two methods have been presented here to equalise the diffraction efficiency across the HOE lens. In the first method, uniformity is improved by selecting a range of spatial frequency in which photopolymer provide almost equal diffraction efficiency. Using experimental data on the spatial frequency at which a fall-off in diffraction efficiency occurs, modelling was carried out in order to design an element that avoided those spatial frequencies. The new HOE lens shows a much-improved uniformity of diffraction efficiency. In the second method, the recording has been done with varying power and exposure time, in order to optimise the diffraction efficiency at the lower spatial frequency. This increases the uniformity of diffraction efficiency across the HOE even when low spatial frequency components are present. The result obtained from the combination of both methods provide HOE lens with overall good and uniform diffraction efficiency. The fabricated HOE lens can be used in focussing as well as a collimating beam for LED application which requires shorter focal length.

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10233-32, Session 6

Hybridization of phase retrieval and off-axis digital holography for high-resolution imaging of complex shape objects

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Digital holography (DH) is a kind of coherent imaging technique. By DH, the intensity and the phase of the object wave can be measured, stored, transmitted, applied to simulations and manipulated in the computer. In off-axis DH, the image is spatially separated from the zero order and twin-image, but the available space-bandwidth product (SBP) of the detector cannot be used efficiently and the resolution is limited. In-line DH has higher utilization of SBP than off-axis DH, but the image and the twin are overlapped. Phase retrieval algorithms were employed to eliminate the twin image in recent years. However, they are only suitable for sparse or transparent objects with a small phase fluctuation.

In this paper, a hybridization method of phase retrieval and off-axis digital holography is proposed for imaging of the complex shape objects. Off-axis digital hologram and in-line hologram are recorded. The approximate phase distributions in the recording plane and object plane are obtained by constrained optimization approach from the off-axis hologram. Then, the approximate phase in the recording plane is used as the initial value in the iterative procedure, and the approximate phase in the object plane is serve as the constraints for retrieve the complex field of the object from the in-line hologram. The complex field in the object plane is gradually approach to the true value during the iterative procedures.

Computer simulations and optical experiments were carried out to validate the hybridization method. The quality of the reconstructed image is improved remarkably in comparison to only in-line or off-axis DH. Furthermore, this method is especially suitable for imaging of complex shape objects.

10233-33, Session 6

Advanced holographic wavefront sensors

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Holographic wavefront sensors provide unique capability of quick, simple and computation-less analysis of the incident wavefront. However, the use of the straightforward record of the overlapped holographic filters results in the strong cross-talk noise, limiting practical implementation of the device. The use of more sophisticated technologies, and in particular of the Fourier holograms, opens the opportunity to reduce or eliminate such noise. The paper considers this technology and describes the results of its numerical and laboratory simulation.

10233-34, Session 7

Properties of diffraction gratings holographically recorded in poly(ethylene glycol)dimethacrylate-ionic liquid composites *(Invited Paper)*

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We investigated recording and readout of transmission gratings in composites of poly(ethylene glycol) dimethacrylate (PEGDMA) and ionic liquids in detail. Gratings were recorded using a two-wave mixing technique at a grating period of about 0.48 and 5.7 micrometers, respectively, employing two different exposures for a series of film thicknesses (10 - 150 micrometers) using a coherent laser beam of 355 nm wavelength.

The recording kinetics as well as the post-exposure behavior of the gratings were studied by diffracting a low intensity probe beam with a wavelength of 633 nm at Bragg incidence. To obtain a complete characterization of the gratings two-beam coupling experiments were conducted to determine the type, the strength and potential relative phases between the recorded gratings. Finally, the angular dependence of the diffraction efficiency was measured for different post-exposure times.

We found that - depending on the parameters - different grating types (pure phase or mixed) are generated, and at elevated thicknesses strong induced light scattering develops. The measured angular dependence of the diffraction efficiency can be fitted using a five-wave coupling theory assuming an attenuation of the gratings along the thickness. Gratings with thicknesses up to 85 micrometers are of good quality and properties. At larger thicknesses light-induced scattering becomes prominent. The obtained results are in particular valuable when considering PEGDMA-ionic liquid composites for applications as e.g. biomaterials, conductive polymers, holographic storage materials and as neutron optic diffractive elements.

10233-35, Session 7

Inline quality control of micro-parts using digital holography

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In this paper we demonstrate a digital holographic system for the fast inspection of the interior of micro parts, which is capable of working in an industrial environment. The use of micro deep drawing parts currently is widely spread in different technology branches. The interior structure is usually highly important for the functionality of those parts. As several hundred micro deep drawing parts can be produced per minute and have dimensions in the mm-range, a precise and fast inspection method is desirable. An automated optical inspection inside the production line serves for quality assurance and reduces the costs and time for a sophisticated manual inspection [1, 2].

Up to now tactile and confocal microscopy methods are commonly used, but are too slow for automated systems. As an alternative method, White Light Interferometry is suitable [3], but requires a mechanically stable environment. Digital Holography is a candidate for three dimensional inspection [4], because it is precise and only requires a small number of recordings to obtain the object shape [5, 6]. With the help of Digital Holography 3D information of the investigated object can be extracted in a single exposure. Keeping the exposure time in the ms-range makes the system insensitive to mechanical distortions. For the investigation of rough objects we use Two-Wavelength-Contouring for the evaluation with a synthetic wavelength of approximately 85 μm.

Special consideration is given to the mechanical robustness of the system. Firstly, we implement the Two-Frame Phase Shifting method for the recording of a complex wavefield. The use of two cameras for different polarized states for the object- and reference wave allows for the recording of a complex wavefield in a single exposure per wavelength. Secondly a Michelson-setup in front of the imaging optics increases the robustness for the measurement as the light paths of the object and reference arm are almost common.

Measurement results allow determining the shape of the interior surface and faults such as scratches with an measurement uncertainty of approximately 5 μm.

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10233-36, Session 7

Hologram calculation technique for viewing-zone scanning holographic display employing MEMS SLM

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Holography is an ideal three-dimensional (3D) image generation technique. However, conventional holographic displays require ultra-high resolution spatial light modulators (SLMs) to provide a large screen size and a large viewing zone. We have developed the viewing-zone scanning holographic displays employing MEMS SLMs, which enlarge the screen size and the viewing zone by use of the high frame-rate image generation by the MEMS SLMs [Opt. Express, vol. 22, 24713 (2014)]. The multi-channel system has also been developed for the scalable enlargement of the screen size; the two-channel system with a screen size of 7.4 in. and a viewing zone angle of 43º was demonstrated [Opt. Express, vol. 24, 18772 (2016)]. In this study, the hologram calculation technique for the viewing-zone scanning system is explained and the fast calculation technique is proposed.

The viewing-zone scanning system is briefly explained. It consists of a MEMS SLM, a magnifying imaging system, and a horizontal scanner. The MEMS SLM generates hologram patterns at a high frame-rate. The generated hologram patterns are enlarged by the magnifying imaging system to increase the screen size. The magnifying imaging system also converges light to generate a viewing zone. Because the pixel pitch is enlarged, the width of the viewing zone is reduced. The reduced viewing zone is then scanned by the horizontal scanner to enlarge the viewing zone.

The hologram calculation technique is explained. The viewing-zone scanning system sequentially generates number of reduced viewing zones at different horizontal positions during each scan and the same number of hologram patterns are displayed by the MEMS SLM. Because the wavefront produced by each hologram pattern is converged to the corresponding reduced viewing zone, the wavefront should be the object wave subtracted by the spherical wave converging to the reduced viewing zone. We found that the subtracted object wave becomes the object wave emitted from the 3D objects which are geometrically transformed referring to the position of the reduced viewing zone. Therefore, the hologram patterns are calculated for the geometrically transformed 3D objects.

In this study, the point-based model is used to represent 3D objects; 3D objects consist of an aggregate of object points. The half zone-plane technique is used to calculate the hologram patterns [Appl. Opt., vol. 48, H64 (2009)], which allows the elimination of the conjugate image and the zero-order diffraction light using a single-sideband filter placed in the magnifying imaging system. The half zone-plates placed at the object points are added to obtain the hologram pattern. In this study, the half zone-plate is modified into the two-line zone-plate because the viewing-zone scanning system provides only horizontal parallax. A one-line zone-plate, which is a one-dimensional zone-plate, can generate an object point. The addition of the complementary line enables the elimination of the conjugate image and the zero-order diffraction light. This modification reduces the amount of calculation by several times, and greatly shortens the calculation time.

10233-37, Session 7

Stereo-hologram in discrete depth of field

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In holographic space, continuous object space can be divided as several discrete spaces satisfied each of same depth of field (DoF). In the environment of wearable device using holography, specially, this concept can be applied to macroscopy filed in contrast of the field of microscopy. Since the former has not need to high depth resolution because perceiving power of eye in human visual system, it can distinguish clearly among the objects in depth space, has lower than optical power of microscopic field. Therefore continuous but discrete depth of field (DDoF) for whole object space can present the number of planes included sampled space considered its DoF. Each DoF plane has to consider the occlusion among the object’s areas in its region to show the occluded phenomenon inducing by the visual axis around the eye field of view. In stereoscopic circumstance, both DDoFs (left and right eye) give the each longitudinal region and make the superposed area at the convergence point. This area would be assumed as the differentiated horopter region in stereoscopic condition. Therefore this region may reduce the perceiving power to recognize the object distinguishable to other objects and it makes easier perceiving process than monocular condition. For this reason, the scenes with DDoF region in whole over the field of view by stereoscopic condition are not same weight to perceiving work, thus the region of interesting to see what will be only selected naturally and the other regions are thrown. Thus the sampling work to make hologram information will be reduced automatically. Therefore both sectioning and understanding of DDoF are very important in stereo-hologram process. Finally, least number of DDoF planes are transformed to their discrete holograms and convoluted. After numerical reconstruction, the inversed convoluted hologram makes natural scene in recognition process even though the combined discontinuous DoF regions are altered to the continuous object space.

DDoF pull out the advantages such as saving consuming time of the calculation process making the hologram and the reconstruction. This approach deals mainly the properties of several factors required in stereo hologram HMD such as stereoscopic DoF according to the convergence, least number of DDoFs planes in normal visual circumstance (within to 10,000mm), the efficiency of saving time for taking whole holographic process under the our method compared to the existing. Consequently this approach would be applied directly to the stereo-hologram HMD field to embody a real-time holographic imaging.

10233-38, Session 7

Comparison of the different approaches to generate holograms from data acquired with a Kinect sensor

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Data of real scenes acquired in real-time with a Kinect sensor can be processed with different approaches to generate a hologram. 3D models can be generated from a point cloud or a mesh representation. The advantage of the point cloud approach is that computation process is well established since it involves only diffraction and propagation of point sources between parallel planes. On the other hand, the mesh representation enables to reduce the number of elements necessary to represent the object. Then, even though the computation time for the contribution of a single element increases compared to a simple point, the total computation time can be reduced significantly. However, the algorithm is more complex since propagation of elemental polygons between non-parallel planes should be implemented. Finally, since a depth map of the scene is acquired at the same time than the intensity image, a depth layer approach can also be adopted. This technique is appropriate for a fast computation since propagation of an optical wavefront from one plane to another can be handled efficiently with the fast Fourier transform.

Fast computation with depth layer approach is convenient for real time applications, but point cloud method is more appropriate when high resolution is needed. In this study, since Kinect can be used to obtain both point cloud and depth map, we examine the different approaches that can be adopted for hologram computation and compare their performance in term of computation speed, and reconstruction quality.

10233-39, Session 7

Transformation of Rozhdestvensky Hooks in digital holographic interferometer

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Digital holography provides a lot of opportunities for transformation of interferometric information. One can increase the interferometer sensitivity by "amplification" of holographic fringes' deformations, remove the distortions, imposed by interferometer elements, provide digital summation or extraction of interferograms, modify the spatial carrier frequency etc. However, to the moment this technique was applied mainly to the interferometers, measuring height of distortions, distance to the object or its movement parameters. We consider the prospects of applying similar approaches in the case of spectroscopy interferometery. This idea was investigated in the experiment with the use of modified Jamin interferometer, working together with spectrograph (this device is also known as Rozhdestvensky interferometer). The results of the experiment has shown that the use of holographic multiplication simplifies the analysis of interferograms, used for investigation of fine structure of spectral lines.

10233-53, Session PS

The schemes and methods for producing of the visual security features used in the color hologram stereography

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Visual security elements used in color holographic stereograms - three-dimensional colored security holograms - and methods their production is describes in this article. These visual security elements include color micro text, color-hidden image, the horizontal and vertical flip - flop effects by change color and image. The article also presents variants of optical systems that allow record the visual security elements as part of the holographic stereograms. The methods for solving of the optical problems arising in the recording visual security elements are presented. Also noted perception features of visual security elements for verification of security holograms by using these elements.

10233-55, Session PS

Design and optimization of a dispersive unit based on cascaded volume phase holographic gratings

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We describe a concept of a dispersive unit consisted of several cascaded volume-phase holographic gratings for spectroscopic applications. Each of the gratings in such unit provides high diffractive efficiency in a relatively narrow wavelength range and almost doesn't affect the beams propagation outside of this region. If a few of such gratings are mounted one after another with proper inclination angles in both of tangential and sagittal planes, it appears to be possible to form a spectral image consisting of several lines and characterized by a relatively high dispersion and high illuminance. We consider a technique of design and optimization of such a scheme. It allows to define modulation of index of refraction and thickness of the holographic layer for each of the gratings as well as their inclination angles. The technique includes two stages: on the first one the gratings parameters are found approximately using analytical expressions of Kogelnik's coupled wave theory, on the second one the values are specified by using of numerical optimization procedure and rigorous coupled wave analysis. We demonstrate this technique on example of a small-sized spectrograph for astronomical applications. It works in the visible domain of 430-680 nm and uses three gratings covering three sub-ranges centered around 472, 555 and 638 nm, respectively. The spectral image consists of three lines with reciprocal linear dispersion of 4.15 nm/mm. The image is characterized by high illuminance and is free of any cross-talks between the lines. It's proved by results of advanced modeling and experiments, which are described in details in our other publications. We consider an ordinary VPH grating

recorded on dichromated gelatin with quasi-sinusoidal fringes profile, but in the last part of the work we study possible improvements of the scheme, which could be implemented with use of modern photopolymer materials. Namely, approaches to sharpen the diffraction efficiency curve's edges are discussed.

10233-56, Session PS

Use of a freeform-shaped holographic grating in a scheme of multislit astronomic spectrograph

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In the present work we consider optical design of a multi-slit astronomic spectrograph for UV domain with freeform reflective elements. The scheme consists of only two elements – a holographic grating imposed on freeform surface and a freeform mirror. The standard Zernike polynomials (up to the 4th order) are used to describe the freeform surfaces shapes. The grating is supposed to be a usual 1st-generation holographic one recorded by two coherent point sources. We demonstrate that in such scheme it's possible to obtain quite high optical quality for an extended field of view and relatively high dispersion. It should be noted, that we consider a relatively slow incident beam with F/# about 17, which is typical for astronomic telescopes. Also, it's supposed that the spectral image is focused on a spherical surface. The current target values of the main parameters are as follows: linear field of view is 76x32 mm, reciprocal linear dispersion is 0.5 nm/mm and resolving power is not less than 15 000 over the UV range of 100-200 nm. Two options are considered: an instrument for measurements of bright objects with a narrow slits and an instrument for faint objects observations with wide slits. In the latter case an accent is put on apertures coupling with the pre-optics. A special attention is payed to imaging properties of the freeform-shaped hologram, its' modeling and optimization. Currently we are working on advanced model of the spectrograph and a more precise evaluation of its' performance will be presented in the manuscript. We suppose, that the optical scheme can be of a special interest for the future space telescopes missions.

10233-57, Session PS

Holography from Venus de Milo to cultural performance, science and technology

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The first hologram in France was performed in Besancon, France. Holography dominates the activity of the laboratory, and in 1975 reached its peak for instance with the hologram of the Venus de Milo, height 1.5m hologram on 1m wide. This, the largest realized at that time,it went around the world. In the following years, holography continues to grow in different directions (art, holographic elements, holographic interferometry, etc.). Meanwhile, the laboratory specializes in holographic interferometry and classic, an area in which it excels today. Leafun demonstration base located in Guangzhou Development Zone, in Guangzhou, China. It is the first demonstration base that combined the most advanced R & D center in the country, laboratories and manufacturing factory into one place. Both French and Chinese partners are following the quest for holography applications in sciences. Most recent realizations will be presented at the conference.

10233-58, Session PS

Multiplexed holograms recorded in a low toxicity biophotopol photopolymer

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Photopolymers are light sensitive materials that have demonstrated its potential use as a recording material due to the advantages of chemical versatility, easy processability and low cost offered by organic materials. These materials are useful for different applications such as in the development of holographic memories, holographic optical elements or as holographic sensors. These photopolymers have good properties, in particular: good energetic sensitivity compared with that of other available materials; the possibility of easily adapting their spectral sensitivity to the type of recording laser used by simple changing the sensitizer dye; high diffraction efficiency, together with an acceptable resolution and signal/noise ratio. There are many types of photopolymers that may be differentiated by the type of binder, since this component determines to a great extent the choice of monomer, dye and initiator used in the photopolymer

Traditionally, polyvinyl alcohol/acrylamide has been considered as a versatile holographic recording material; however, this type of photopolymer has low environmental compatibility. Instead, our team has been developing during the last years a biodegradable and biocompatible photopolymer called Biophotopol which has been showed high diffraction efficiency (with reported values near 90%) in 300 ?m thick layers. In this work, we have evaluated the capacity of store gratings at a single location. Thereby, fifteen gratings have been recorded by combining parallel and perpendicular multiplexing techniques. Five gratings for each perpendicular multiplexed position were stored with an angular separation of 1º along the parallel axis. The angular separation between each perpendicular axis position was 10º. In order to store gratings with uniform diffraction efficiency the exposure times were adjusted by following an iterative method. The accumulated dynamic range obtained for the Biophotopol sample was M#=5.3.

We have assessed the Biophotopol's grating stability doing the reconstruction of the holograms and analyzing the variation of the maximum diffraction efficiency over the time. Thirteen holograms were stored at a single location in steps of 3º using the axis parallel to the sample plane. Over a period of ten months the maximum diffraction efficiency values fluctuated around the initial values. This variation depended on the initial maximum diffraction efficiency, the temperature and relative humidity conditions. These variations could allow us to use Biophotopol photopolymer as a sensor.

In this study we demonstrated the storage capacity of Biophotopol as a recording material together with its potential application as multiplexing photopolymer material. Its performance is comparable to that of to the AA based photopolymer in this type of applications, with the added advantage of its low toxicity.

10233-59, Session PS

Diffractive axicon with tunable fill factor for focal ring splitting

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We have considered effect of fill factor of circular binary phase grating on intensity distribution in the focal plane. A theoretical analysis is performed in two approaches. One of them allows describe the general distribution structure in the focal plane, but it is not suitable for solving the inverse problem. The second approach allows us to explain the fine structure in the intensity maxima corresponding diffraction orders. In particular, this approach explains the possibility of focal ring splitting and allows to calculate the ratio of the intensities of the two rings. The theoretical calculations and numerical simulation confirmed by experimental studies. As a result, we have shown the ability to dynamically change the focal structure due to regulation of the grating's fill factor by means of a spatial light modulator.

10233-60, Session PS

Characterization of a photopolymer holographic recording material for concentrator and space applications

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In space environment, the photovoltaic(PV) cells are very important for both life and good operation of the satellite inasmuch they have to be able to convert solar energy in electrical energy. Actually, one of the challenges for missions in space, included the launch of a satellite, is the huge cost for the PV cells. In the scientific and industrial community, reduction of the cost of the cells is one of the most challenging aims and one possibility is to find alternative technological solutions. One of these is the use of solar concentrators, in particular the use of holographic solar concentrators realized thanks to holographic optical elements(HOE): holographic lenses and volume holographic grating (VHG). For recording of two different holograms we will utilize a new prototypal material photosensitive to green light. The material was based on a sol-gel matrix formed by condensation of alkoxysilanes functionalized with organic pendant groups and they are characterized by interpenetrating organic and inorganic networks. After recording holographic lenses and volume holographic gratings, we will characterize the new holographic material for space applications[1,2,3].

In particular, after writing HOE in transmission and in reflection mode of recording, the diffraction efficiency will be assessed, in both configurations, according to the following relationship: ??=??1/(??0+??1), (1)

where P1 is the measured power of the 1st diffraction order and P0 is the measured power of the zero diffraction order.

Then, we will evaluate the thermal stability of the gratings by measuring variation of efficiency due to the change in the temperature of the photopolymer, simulating the extreme temperatures in the environment space. In addition, we will evaluate the diffraction efficiency by varying either incident light energy on the material or exposure writing times [4,5]. Finally, we will perform other three characterizations which consist of a study of the material refractive index variation as a function of the exposure energy, a surface characterization of the HOE with the Atomic Force Microscope(AFM) and an outgassing test to verify the use of this material for space applications [3,4].

In conclusion, we will present a comprehensive characterization of a new material and the possibility of its use as recording material for efficient holographic solar concentrators that could be used in space applications.

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10233-61, Session PS

Photopolymer film-based holographic optical element for modification of LED radiation pattern

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Holographic diffraction elements (HDEs) such as volume phase diffraction gratings, various information-processing elements and holographic lenses offer attractive advantages compared to conventional optical elements which employ refraction or reflection of light. An efficiency of transformation of an incident wavefront into a desired output wavefront as high as 100% can be achieved in a proper medium even with thickness of the order of tenths of micrometers. The advantage of such thickness is in a low weight of the single element and feasibility to form complex structures with more compact sizes, as well. Utilization of proper holographic materials like photopolymers also offers a possibility of mass production via process of replication. Application for the research presented in this paper is intended for lighting industry, in particular to reduce divergence of light emitting from a monochromatic LEDs, which are good Lambertian radiators. Current state of the art solutions employ reflectors, lenses – either Total Internal Reflection (TIR) or Fresnel lenses –, or micro prismatic diffusers with submilimeter size of the prisms. These solutions are either bulky or do not hold versatile light control ability failing to achieve ultra-narrow beams, i.e. half value luminous intensity apex angle below 12 degrees, and may lead to luminance non-uniformity of footprint. On top of that light propagation control capabilities of the refractors are degraded due to dust deposition on the refractive surfaces. Optical components with superior light propagation control for modern light sources therefore should be made of finer diffraction pattern which should be located within material. This could be achieved by holographic diffraction elements.

This paper reports on recording of interference pattern of collimated and divergent helium neon laser beams as reference and object beams respectively in a photopolymer holographic recording material. The aim is to produce a holographic optical element (HOE) capable to modify radiation pattern of a monochromatic LED efficiently. The mutual alignment of optical components such as mirrors and beam splitters used for recording forms Mach-Zehnder interferometer which allows for recording a holographic optical element in both, transmission and reflection geometries. Firstly, the proper experimental conditions for recording are determined via recording the quasi-harmonic volume phase diffraction gratings (Bragg gratings) and analyzing their diffraction efficiencies according to Kogelnik’s theory. From the obtained response curve (dependence of the refractive index modulation on the exposure time) for wavelength 514 nm and fixed recording intensity the proper recording conditions are chosen and the holographic optical element is formed in the photopolymer film accordingly. The performance of the produced HOE is demonstrated in two ways: (i) HOE’s diffraction efficiency is directly measured; (ii) the radiation pattern of tested LED with applied holographic optical element is measured and compared with a radiation pattern of the single LED when no HOE is applied. According to the results obtained one can decide whether the used holographic photopolymer film meets criteria for the purpose of creating holographic optical elements. At the same time one can compare the diffraction efficiencies of the HOE’s prepared by different recording geometries and choose a more appropriate one.

10233-62, Session PS

Optical-electronic device on the basis of diffraction optical element for control of special protective tags executed from luminophor

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This report focuses on special sphere of polygraphy, which is called protected polygraphy. It uses polygraphic methods for protection against forgery or falsification of protected polygraphic products. There are banknotes, securities, identity documents (passports, certificates, diplomas, different certificates, etc.), travel checks, lottery tickets and other polygraphic products, which need to be protected from a forgery or falsification. One of the most perspective directions in the protected polygraphy is the creation of machine-readable signs on the basis of the luminophor, that have Stokes (in IR of area of a range) and anti-Stokes (in visible area of a range) components.

Such luminophors are colourless therefore they can be implemented in paper, paint, protective thread and any other element of the protected product without changing its optical properties.

In the report we considered the possibility of creation of the spectral device for determination of authenticity of these or those documents which are protected by means of machine-readable luminiferous tags. The device works in two spectral ranges - visible and NIR. That allows to register stokes and anti-stokes having spectral components of protective tags. Determination of authenticity of the document is based on a test sample with the standard parameters and the characteristics which are recorded in the memory of the device, according to the following criteria: a coincidence of the spectral characteristics, of the energy and time parameters buildup and decay of luminescence emission with a predetermined accuracy. As the dispersing elements of optic-electronic device have been chosen acousto-optic crystal in IR channel and concave diffraction grid in the visible channel.

The device allows to conduct the authentication of protected polygraphic products according to several criterions in different spectral ranges. It can be used at the enterprises which are involved in the manufacture of protected polygraphic products, in expert law enforcement agencies engaged in checking of the authenticity of banknotes and in other structures.

10233-63, Session PS

Observation of neutron pendellösung-interference in holographic nanostructures

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We aim at advancing neutron optics for improving and developing novel methods of neutron scattering, diffraction and spectroscopy. For that purpose, we employ nanoparticle-polymer composite grating-structures fabricated by optical holography. Previous experiments with such gratings have demonstrated that they can be used as (multi-port) beam-splitters or mirrors with up to 90 % reflectivity for cold or very-cold neutrons, which was achieved exploiting the Pendelloesung interference effect by increasing the effective thickness of the gratings by tilting.

In recent experiments, we have observed full Pendelloesung oscillations of intensity between the diffracted and the forward-diffracted beam due to internal interference in the holographic nanostructures' periodic potentials. The results pave the way for applications like small-size and cheap polarizing beam-splitters for small-angle neutron scattering or in fundamental science.

10233-64, Session PS

True colour Denisyuk-type hologram recording in Bayfol HX self-developing photopolymer

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Realistic true colour reproduction is one of the relevant objectives of holography. The most commonly used recording technique is Denisyuk's single beam configuration. Numerous studies have been conducted to optimize the recording in silver halide materials.

A new panchromatic self-developing photopolymer, Bayfol HX, developed by Covestro (formerly Bayer MaterialScience) permits the recording of colour holograms. Its sensitivity ranges from 400 to 700 nm.

Monochromatic Denisyuk holograms of a standard white diffuser (Spectralon) have been recorded in Bayfol HX 102 using lasers with wavelengths 441.8, 532 and 633 nm to determine the optimum exposure that gives maximum efficiency. The recording of holograms from a diffusing object has the particularity that intermodulation noise due to interference between waves arriving from different object points reduces effective index modulation. A maximum effective efficiency of 80% has been reached for monochromatic recording.

A theoretical model has been developed that takes into account the effective index modulation produced by the intermodulation noise, and the threshold exposure that starts the self-polymerization of the material.

This theoretical model has been applied to determine the maximum efficiency obtainable for three-wavelengths simultaneous recording, deducing that an upper limit near 20 % is reachable for each wavelength.

A set of experiments has been carried out to determine the adequate relation of exposure for the recording of a Denisyuk hologram of the standard white diffuser with the three lasers simultaneously to get the maximum theoretical efficiency for each wavelength.

With the determined optimal exposure, a hologram of a polychromatic diffusing object has been recorded, obtaining a good visual coincidence between hologram and original object.

10233-65, Session PS

Constraints to solve parallelogram grid problems in 2D nonseparable linear canonical transform

Liang T. Zhao, John J. Healy, Inbarasan Muniraj, John T. Sheridan, Univ. College Dublin (Ireland)

The 2D non-separable linear canonical transform (2D-NS-LCT) can model a range of various paraxial optical systems. Digital algorithms to evaluate the 2D-NS-LCTs are important in modeling the light field propagations and also of interest in many digital signal processing applications. In [Zhao 14] we have reported that a given 2D input image with rectangular shape/boundary, in general, results in a parallelogram output sampling grid (generally in an affine coordinates rather than in a Cartesian coordinates) thus limiting the further calculations, e.g. inverse transform. One possible solution is to use the interpolation techniques; however, it reduces the speed and accuracy of the numerical approximations. To alleviate this problem, in this paper, some constraints are derived under which the output samples are located in the Cartesian coordinates. Therefore, no interpolation operation is required and thus the calculation error can be significantly eliminated.

10233-66, Session PS

A digital holographic approach for the analysis of phase patterns in photochromic polyurethanes

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Photochromic materials show a reversible change in their color upon photoirradiation with suitable light (UV and visible). A reversible modulation of refractive index in the Vis-NIR spectral region also occurs

in the photochromic materials. In the case of photochromic polyurethanes based on diarylethene moiety the change of the refractive index is large (of the order of 0.01) thanks to the large content of photochromic unit in the polymeric film. It is therefore possible to write phase patterns in such films, but it is also important to characterize the phase patterns. Here, patterns at the micron scale range have been written by a suitable direct laser writing machine based on a red laser and characterized at 1550 nm by means of a digital holographic approach. The choice of such wavelength in the NIR for characterizing the photochromic patterns is necessary to avoid the erase of the patterns, which would occur using visible lasers. The holographic imaging has been obtained by means a Mach-Zehnder configuration. In particular, the laser light has been split in two beams by a polarized beam splitter. One beam has been used as reference; the second beam (object beam) illuminates the photochromic material through a microscope objective. A second beam splitter has been used to recombine the two beams and create a hologram. By means of a numerical approach the hologram has been elaborated and the refractive index profile has been retrieved. Moreover, the dependence of the refractive index on the film thickness and photochromic content and the writing speed has been investigated. The writing process has been modelled by means of a kinetic model, showing theoretically the dependence of the pattern width and profile with the writing condition. It is demonstrated how the photochromic films are suitable for developing a reconfigurable platform for complex phase patterns working in the NIR and how the digital holography in the NIR is a powerful and reliable technique to characterize such systems.

10233-67, Session PS

Study of interference of optical coherence functions by using coherence holographic interferometry

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Interference, where the superposition of two or more waves resulting in a new wave pattern, has been considered as one of the most important and fundamental physical phenomenon. In optics, the statistical properties of light play an important role in determining the outcome of most optical experiments and the cross correlation between the fluctuating fields at different space time points, known as the optical coherence functions is a quantity of great interest. Due to the fact that the wave equations govern propagation of optical coherence, it can be envisaged that the interference phenomena also appear in the format of the optical coherence function. Meanwhile, the study of propagation and superposition of optical coherence function also provides theoretical and experimental foundations for coherence holography.

In this paper, we have given the mathematical expression of interference of the optical coherence functions, and have proposed a full-field coherence visualization system for coherence holographic interferometry. The interference of two optical coherence functions has been experimentally investigated which can be regarded as an extension of Young's double-slit interferometer for optical waves. Some interesting phenomena, such as missing class of the coherence function and multiple-coherence function interference are demonstrated for the first time.

10233-68, Session PS

Optical recording in functional polymer nanocomposites by multibeam interference holography

Dmitrij Zhuk, Julia A. Burunkova, Viacheslav Kalabin, ITMO Univ. (Russian Federation); Istvan Csarnovics, Sandor J. Kokenyesi, The Univ. of Debrecen (Hungary)

New materials and technologies are under development last time for fabrication of photonic elements like gratings, integrated elements, photonic crystals. Among the wide number of materials and proper fabrication methods holographic recording in photo-sensitive polymers is one of the most known, although the selective etching, development of optical reliefs causes essential shortcomings.

The goal of the present work was the development and application of the multi-beam interference method for one step, direct formation of 1-, 2- or even 3D photonic structures in functional acrylate nanocomposites, which contain $SiO2$ and Au nanoparticles and which are sensitized to blue and green laser illumination.

Due to the presence of gold nanoparticles plasmonic effects can essentially influence the polymerization processes and the spatial redistribution of nanoparticles in the nanocomposite during the recording. It is essential, that no additional treatments of the material after the recording are necessary and the elements possess high transparency and low scattering levels. New functionalities can be added to the recorded structures this way, enabling the creation of photonic, sensor structures with switchable parameters.

10233-15, Session 8

Photopolymers for holographic optical elements in astronomy

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Holographic Optical Elements cover nowadays a relevant position as dispersing elements in astronomical spectrographs because each astronomical observation could take advantage of specific device with features tailored for achieving the best performances.

The design and manufacturing of high efficiency and reliable dispersive elements require photosensitive materials as recording substrate, where it is possible to precisely control the parameters that define the efficiency response (namely both the refractive index modulation and the film thickness).

The most promising materials in this field are the photopolymers because beside the ability to provide the tuning feature, they bring also advantages such as self developing, high refractive index modulation, and ease of use thanks to their simple thin structure, insensitive from external environment.

In particular, we studied the photopolymers provided by Covestro AG, namely Bayfol® HX, which were characterized with the purpose to use them as new material for astronomical Volume Phase Holographic Gratings.

We designed and manufactured VPHGs for astronomical instrumentation and we demonstrated how photopolymers are reliable holographic materials for making astronomical devices with performances comparable to those provided by VPHGs based on Dichromated Gelatins (DCGs), but with a much simpler production process.

Moreover, the versatility of these materials allowed us to propose and realize novel architectures of the spectroscopic dispersive elements. A compact and unique single prism device was realized for a FOSC spectrograph and new multi-layered devices are proposed, stacking VPHGs one on top of the other to obtain many spectra in the instrument's detector, with advantages as increase of resolution and signal to noise ratio with respect to the classical single dispersive element.

10233-41, Session 8

Energy analysis of holographic lenses for solar concentration

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The use of volume and phase holographic elements in the design of photovoltaic solar concentrators has become very popular as an alternative solution to refractive systems, due to their high efficiency, low cost and possibilities of building integration. Angular and chromatic selectivity of volume holograms can affect their behavior as solar concentrators. In holographic lenses, angular and chromatic selectivity varies along the lens plane. Besides, considering that the holographic materials are not sensitive to the wavelengths for which the solar cells are efficient, the reconstruction wavelength is usually different from the recording one. As a consequence, not all points of the lens work at Bragg condition for a defined incident direction or wavelength.

A software tool that calculates the direction and efficiency of solar rays at the output of a volume holographic element has been developed in this study. It allows the analysis of the total energy that reaches the solar cell, taking into account the sun movement, the solar spectrum and the sensitivity of the solar cell. The dependence of the recording wavelength on the collected energy is studied with this software.

As the recording angle is different along a holographic lens, some zones of the lens could not act as a volume hologram. The efficiency at the transition zones between volume and thin behavior in lenses recorded in Bayfol HX is experimentally analyzed in order to decide if the energy of generated higher diffraction orders has to be included in the simulation.

10233-42, Session 8

Full-color large-scaled computer-generated holograms for physical and nonphysical objects

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We present techniques for creating very large scaled computer-generated holograms (CGH), which are composed of several tens of billions of pixels and able to reconstruct full-color full-parallax 3D images. These large-scaled CGHs, referred to as high-definition CGHs, have a large space-band product. Multiple viewers can see the 3D image simultaneously, because the size is more than several tens square centimeters and their viewing angle is more than 45 degrees in both horizontal and vertical directions.

The object field used for generating CGHs is obtained from several techniques; that is, computer graphics (CG) for non-physical objects, high-density digital holography (DH) and multiple-viewpoints images (MVI) for physical objects. The object fields obtained from these different digital data-sources are integrated in a virtual 3D scene and produce the 3D image.

The object field of non-physical CG-models is calculated by the polygon-based method or point cloud. The 3D model data is sometimes acquired by using 3D scanner. In this case, the reconstructed images are of the physical object with slightly deform. The fields of physical objects are also acquired by synthetic-aperture-based large-scale DH. In this case, the whole process in classical holography, i.e. recording and reconstruction, is replaced by its counterparts in digital technology. Thus, we refer to the technique as digitized holography. It is ideally expected that the digitized holography gives perfect reconstruction of light of physical objects. However, the technique is practically too difficult to record and reconstruct light of a large object in full-color. Therefore, the object field generated from MVIs are also used for producing 3D images of large objects or scenes. In this case, we used the ray-sampling plane technique to compute the field from MVIs.

Mutual-occlusions between the objects, whose fields is calculated or captured by above techniques, are processed with a mask-based technique called the silhouette method. In addition, self-occlusions in the CG-modeled object are also processed by the silhouette method with the switch-back technique. These techniques provide continuous and natural motion parallax to the CGHs and bring strong sensation of depth to viewers.

The full-color reconstruction of the CGH is realized by using RGB color filters similar to that used in LCD panels and image sensors. In practice, the RGB color filters are fabricated by the same technique as these. In combination with three-chips type white LEDs, we can get sufficiently narrow band illumination for reconstructing good full-color 3D images. Actual full-color high-definition CGHs created by these techniques will be demonstrated in the meeting.

10233-43, Session 8

High quality digital holographic reconstruction on analog film

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High quality real-time digital holographic reconstruction has been at the forefront of research in the field of holography and has been hailed as the holy grail of display systems. While these efforts have produced a fascinating array of computer algorithms and technology, there are many applications of reconstructing high quality digital holograms do not require such high frame rates. In fact, applications such as 3D holographic lithography may even require a stationary mask. One common class of devices used for digital hologram reconstruction are based on spatial light modulator technology and which is great for reconstructing arbitrary holograms on the fly; however, it lacks the high spatial resolution achievable by its analog counterpart, holographic film. Analog holographic film is therefore the method of choice for reconstructing high quality static holograms. The challenge lies in taking a high-quality, digitally calculated hologram and effectively writing it to holographic film. We have developed a system based on an electronically tunable phase plate, an intensity adjustable high-coherence laser and a 2D galvo scanning head to effectively write a digitally calculated hologram on analog film. The system works by reproducing the individual components, both the amplitude and phase, of the hologram in the Fourier domain. These Fourier components are then interfered with a reference beam and individually written on the holographic. While creating the hologram in this manner does not return the exact mathematical description of a hologram, the important parts, such as the real and virtual reconstructed wavefront can still be produced.

10233-44, Session 8

Information recovery in propagation-based diffraction imaging with decoherence effects

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During the past decades the optical imaging community witnessed a rapid emergence of novel imaging modalities such as coherent diffraction imaging (CDI) [1], propagation-based imaging [2] and ptychography [3]. These methods have been demonstrated to recover complex-valued scalar wave fields from redundant data without the need for refractive or diffractive optical elements [4]. This renders these techniques suitable for imaging experiments with EUV and X-ray radiation, where the use of lenses is complicated by fabrication, photon efficiency and cost. However, decoherence effects can have detrimental effects on the reconstruction quality of the numerical algorithms involved.

Here we demonstrate propagation-based optical phase retrieval from multiple near-field intensities with decoherence effects such as partially coherent illumination, detector point spread, binning and position uncertainties of the detector. Methods for overcoming these systematic experimental errors - based on the decomposition of the data into mutually incoherent modes - are proposed and numerically tested. We believe that the results presented here open up novel algorithmic methods to accelerate detector readout rates and enable subpixel resolution in propagation-based phase retrieval. Further the techniques are straightforward to be extended to methods such as CDI, ptychography and holography.

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10233-45, Session 9

2D nonseparable linear canonical transform (2D-NS-LCT)-based cryptography

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The 2D non-separable linear canonical transform (2D-NS-LCT) can describe a variety of paraxial optical systems. Digital algorithms to numerically evaluate the 2D-NS-LCTs are not only important in modeling the field propagations but also of interest in various signal processing based applications, for instance optical encryption. Therefore, in this paper, for the first time, a 2D-NS-LCT based optical Double-random-phase-encryption (DRPE) system is proposed which offers encrypting information in multiple degrees of freedom. Compared with the traditional systems, i.e. (i) Fourier transform (FT); (ii) Fresnel transform (FST); (iii) Fractional Fourier transform (FRT); and (iv) linear canonical transform (LCT), based DRPE systems the proposed system is more secure and robust as it encrypts the data with more degrees of freedom and extends the key required.

10233-46, Session 9

Test of VPHGS in SHSG for use at cryogenic temperatures

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Silver halide sensitized gelatin (SHSG) processes are interesting because they combine the spectral and energetic sensitivity of a photographic emulsions with the good optical quality and high diffraction efficiency of dichromate gelatin (DCG).

Previous papers had been demonstrated that it is possible to obtain diffraction efficiencies near to 90% with Agfa-Gevaert plates and Colour Holographic plates in SHSG transmission gratings.

In this communications we report on the performances measured at room temperature and in cryogenic conditions of a set of volume phase holographic gratings(VPHGs) manufactured with SHSG process aimed at their use in astronomical instrumentations. Two set of diffraction gratings has been manufactured using different processing. The first with SHSG process and the second with typical bleached process (developed with AAC and bleached in R-10).

In both cases the plate was BB640, ultrafine grain emulsions with a nominal thickness of 9 μm. The recording was performed with asymmetric geometry an 30º degrees between the light beams of wavelength 632.8 nm (He-Ne laser), which give a raise a spectral frequency of 1000 l/m. The exposure was between 100 to 3000 μJ/cm2.

The measurements have been made in the optics laboratory at the IAC.

The mechanical setup consists in a stable assembly, where all movements are computer controlled.

The optomechanical setup can be described as follows, end to end: a white light source (5A); a motorized beam chopper; an entrance slit; a monochromator; an exit slit; a collimating lens; a diaphragm of the grating size; the grating mounted on 2D (XY) motorized table; a focusing lens and a solid state Si detector on computer controlled rotary table.

The measurements have been taken in the spectral range between 400nm and 1100nm, with a diffracted angle have been between 18º and 42º. All test runs have included a reference measurement, off grating, before and after the grating test.

The measuring routine is as follows. First, the diffracted beam is recorded for each grating covering the full wavelength range for a given exit angle. Then, the measurement is repeated in angular steps to cover the angular range. Then, the grating is cooled down till liquid nitrogen temperature within a cryostat. With the use of a temperature sensor, it is checked that the cooling rate is sufficiently smooth and that the grating reaches 77ºK.

After that, the grating is warmed up till room temperature, and the measurements are repeated following the same sequence as before.

The results give us information about Bragg plane modification and reduction of diffraction efficiency when we introduced the VPHG to 77º K. In the case of SHSG process the final diffraction efficiency after cryogenic temperature are better at some exposure energy than previous measurements at room temperature. This experimental results give us possibilities to applied SHSG process in Astrophysics applications.

10233-47, Session 9

Enhancing performance of LCoS-SLM as adaptive optics by using computer-generated holograms modulation software

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In Liquid Crystal on Silicon (LCoS) technology, different voltages lead different degree of twist of liquid crystal molecules. The light will have phase retardation when it passes through liquid crystal layer. By this effect, amplitude modulation and phase modulation could be implemented, so LCOS could be regarded as spatial light modulator (SLM). SLM is a useful and powerful optical instrument to modulate the optical wavefront and has been widely used on various applications. LCoS-SLM is capable of accepting a video signal and converting it into a holographic image. The video signal, also called Computer Generated Holography (CGH), is one method to generate holographic interference patterns digitally. Moreover, there are three steps to generate CGH, such as computing the virtual scattered wavefront, encoding the interference pattern, and reconstructing the holographic image. Due to the precision wavefront control, LCoS-SLM could be used on adaptive optics (AO) technology. The applications of adaptive optics include beam shaping, vision science, clinical vision science, microscopy, laser communication, and retinal imaging, etc.

In this paper, we develop a multi-function and easy-to-use modulation software that was based on LabVIEW system. There are mainly four functions in this modulation software, such as CGH generation, CGH reconstruction, image trimming, and special phase distribution. Regarding the function of CGH generation, there are various parameters could be adjusted. For example, the wavelength of laser source, pixel pitch, calculated loop number, image position, negative pattern, rotate canvas, etc. Regarding the function of CGH reconstruct image, we can download a CGH image and simulate the diffraction pattern at different distance. Regarding the function of image trimming, there are various CGH patterns could be generated and could be used like diffraction optical elements (DOE). For example, these six CGH patterns are used on prism phase, Fresnel lens, astigmatism, coma & trefoil, gamma correction, negative, cycle, and mirror, etc. Regarding the function of special phase distribution, this software system could provide blank phase, axicon & vortex phase, binary grating, sinusoidal grating, and aperture, etc. Based on the above development of CGH modulation software, we could enhance the performance of LCoS-SLM as similar as the DOE and use it on various AO applications.

However, through the development of special phase distribution, we are going to use the LCoS-SLM with CGH modulation software into AO technology, such as optical microscope system. When the LCOS-SLM panel is integrated in an optical microscope system, it could be placed on the illumination path or on the image forming path. For the first case, we could produce sophisticated illumination patterns or dynamically steerable illumination sources. As a result, the resolution could be enhanced. For the second case, we introduce Fourier filtering technology into the system, and thus the image contrast will be improved. In addition, LCOS-SLM also has the ability to adaptively correct the aberrations introduced by the optical components of system. In brief, LCOS-SLM provides a program-controllable liquid crystal array for optical microscope. It dynamically changes the amplitude or phase of light and gives the obvious advantage, “Flexibility”, to the system.

10233-48, Session 9

Clustering of red blood cells using digital holographic microscopy

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Digital Holographic microscopy can provide quantitative phase images (QPI) about the 3D profile of red blood cell (RBC) with nanometer accuracy. In this paper we propose applying k-means clustering method to classify RBCs into two groups of young and old cells by using a four-dimensional feature vector. The features are RBC thickness average, surface area-volume ratio, sphericity coefficient and RBC perimeter that can be measured from the phase values. The proposed features are related to the morphology of RBC. To evaluate the performance of the proposed technique Calinski-Harabasz clustering evaluation criterion is calculated. The experimental result shows that two clusters can provide the highest output for the clustering validation criterion.

10233-49, Session 9

Terahertz-computed tomography in 3D using a pyroelectric array detector

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Terahertz frequency range spans from 0.1 to 10 THz. Terahertz radiation can penetrate nonpolar materials and nonmetallic materials, such as plastics, wood, and clothes. Then the feature makes the terahertz imaging have important research value. Terahertz computed tomography makes use of the penetrability of terahertz radiation and obtains three-dimensional object projection data. In the paper, continuous-wave terahertz computed tomography with a pyroelectric array detector is presented. Compared with scanning terahertz computed tomography, a pyroelectric array detector can obtain a large number of projection data in a short time, as the acquisition mode of the array pyroelectric detector omit the projection process on the vertical and horizontal direction. With the two-dimensional cross-sectional images of the object are obtained by the filtered back projection algorithm. The two side distance of the straw wall account for 80 pixels, so it multiplied by the pixel size is equal to the diameter of the straw about 6.4mm. Compared with the actual diameter of the straw, the relative error is 6%. In order to reconstruct the three-dimensional internal structure image of the straw, the y direction range from 70 to 150 are selected on the array pyroelectric detector and are reconstructed by the filtered back projection algorithm. As the pixel size is 80?m, the height of three-dimensional internal structure image of the straw is 6.48mm. The presented system can rapidly reconstruct the three-dimensional object by using a pyroelectric array detector and explores the feasibility of on non-destructive evaluation and security testing.

10233-50, Session 10

Phyllotactic arrangements of optical elements

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Phyllotaxy studies arrangements of biological entities, e.g. a placement of seeds in the flower head. Vogel (1979) presented a phyllotactic model based on series of seeds ordered along a primary spiral. This arrangement allows each seed to occupy the same area within a circular flower head. Recently, a similar arrangement of diffraction primitives forming a planar relief diffractive structure was presented. The planar relief structure was used for benchmarking and testing purposes of the electron beam writer patterning process. This contribution presents the analysis of local periods and azimuths of optical phyllotactic arrangements. Two kinds of network characteristic triangles are introduced. If the discussed planar structure has appropriate size and density, diffraction of the incoming light creates characteristic a phyllotactic diffraction pattern. Algorithms enabling the analysis of such behavior were developed and they were validated by fabricated samples of the relief structure. Combined and higher diffraction orders are also analyzed. The phyllotactic arrangement of optical primitives has several interesting properties. One of them concerns the relation between the microscopic parameters of individual optical primitives and the properties of visually perceived images crated by these structures. Other interesting properties comprise partial self–similarity and rotational symmetry of the phyllotactic diffraction pattern. Different approaches enabling the creation of phyllotactic diffractive patterns are proposed. One of the approaches concerns the nesting of two or more phyllotactic models with a distinctively different grain fineness. E–beam lithography is a flexible technology for various diffraction gratings origination. The e–beam patterning typically allows for the creation of optical diffraction gratings in the first diffraction order. Nevertheless, this technology enables also more complex grating to be prepared, e.g. blazed gratings and zero order gratings. Moreover, the mentioned kinds of gratings can be combined within one planar relief structure. The practical part of the presented work deals with the nano patterning of such structures by using two different types of the e–beam pattern generators. One of them is a system with a variable shaped beam of electrons, while the other one is a system with a Gaussian–shaped beam. Finally, we discuss some aspects concerning the e–beam origination and related technological processes. Writing strategies and the use of inherent spiral patterns for the partitioning and the ordering of e–beam exposures are presented. Variations in design parameters include the tone of the structure (positive or negative), the density of filling, the filling factor, and the depth of the structures. The achieved gamut of colors may by primarily extended by the proper selection of metal deposition technology and its parameters, and further by the proper selection of the metal and the thickness of its layer.

10233-51, Session 10

Fast calculation of computer-generated spherical hologram by spherical harmonic transform

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A spherical hologram is very important in terms of the viewing zone enlargement. Viewers can observe three-dimensional (3-D) objects through the spherical hologram from anywhere. This paper presents a fast calculation method for spherical computer-generated hologram based on spherical harmonic transform. A 3-D object is defined in the Cartesian coordinate system and is Fourier-transformed by using a 3-D fast Fourier transform. Then, the spherical Fourier components on the spherical surface, which is defined in the 3-D polar coordinate system, are extracted from the calculated 3-D Fourier spectrum. The wavefront on an arbitrary point in the 3-D real space can be obtained by calculating the sum of products between the spherical Fourier components on the spherical surface and the kernel function. The kernel function is determined by the wavelength and the diffraction distance. The diffraction distance is constant in the case of the diffraction onto the spherical observation surface. Since the kernel function is circular symmetric on the spherical surface, the sum of products between the spherical Fourier components of the 3-D object and the kernel function can be regarded as rotation invariance on the spherical surface. Thus, the calculation of the sum of products is expressed in the form of a convolution integral on the sphere. It should be noted here that in general the convolution theorem comes into effect in such a convolution integral. This means that it is possible to calculate the convolution integral in the same manner as the well-known convolution integral on a planar surface. The difference is that the mathematical transformation is spherical harmonic transform in the convolution theorem on the sphere whereas that is Fourier transform

in the convolution theorem on the planar surface. Some libraries for the fast calculation of the spherical harmonic transform are available. In this paper, in order to verify our proposal, a numerical demonstration has been performed. A 3-D object is defined in the Cartesian coordinate and then the wavefront on the spherical observation surface is calculated at high speed according to our proposal. Approximately 1000 times as fast calculation as the direct calculation method has been achieved. Our proposal is very effective to realize a natural 3-D display with perfect viewing zone.

10233-52, Session 10

Optical position encoder based on four-section diffraction grating

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Optical position encoder consists of movable coding grating and fixed analyzed grating. Light passing and diffracting through these two gratings creates interference signal on optical detector. Decoding of interference signal phase allows to determinate current position. Known optical position encoders use several accurate adjusted optic branches and detectors to gather several signals with different phase for higher encoder accuracy. We propose to use one optic brunch with several-section analyzed diffraction grating for this purpose to simplify optical scheme and adjusting requirements. Optical scheme of position encoder based on four-section analyzed diffraction grating is developed and described in this paper.

10233-54, Session 10

Compressive self-interference Fresnel digital holography with faithful reconstruction

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Self-interference digital holography is an attractive technology and has been applied to three-dimensional fluorescent microscopy, white light color holographic display and adaptive optics etc. The hologram of a point-object originating from an incoherent object can be formed based on spatial self-coherence of the beams by suitable optical beam-splitting skills. The hologram of the extended object is the incoherent superimposion of all point-holograms. Three-dimensional information of the spatially incoherent object can be retrieved by the numerical reconstruction of the digital hologram which is captured by a charge coupled device (CCD). We developed compressive self-interference digital holographic approach that allows retrieving three-dimensional information of the spatially incoherent objects from single-shot captured hologram. The Fresnel incoherent correlation holography is combined with parallel phase-shifting technique to instantaneously obtain spatial-multiplexed phase-shifting holograms. The recording scheme are explained as compressive forward sensing model, thus the compressive-sensing-based reconstruction algorithm is implemented to reconstruct the original object from the under sampled demultiplexed holograms. Four under-sampled phase-shifted holograms are demultiplexed from a single-shot captured interference pattern recorded by an image sensor with polarization array. The object is faithfully reconstructed with a CS algorithm. The concept was verified by simulations and experiments with simulating use of the polarizer array. Through four holograms are recorded sequentially in the experiments, the concept of accuracy reconstruction the object information using CS has been proofed. The proposed technique has great potential to be applied in 3D tracking of spatially incoherent samples.

Conference 10234: Relativistic Plasma Waves and Particle Beams as Coherent and Incoherent Radiation Sources

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10234-1, Session 1

Betatron x-ray radiation in the self-modulated regime of laser-wakefield acceleration

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Betatron x-ray radiation, driven by electrons from laser-wakefield acceleration, has unique properties to probe high energy density (HED) plasmas and warm dense matter. Betatron radiation is produced when relativistic electrons oscillate in the plasma wake of a laser pulse. Its properties are similar to those of synchrotron radiation, with a 1000 fold shorter pulse. This presentation will focus on the experimental challenges and results related to the development of betatron radiation in the self modulated regime of laser wakefield acceleration.

We observed multi keV Betatron x-rays from a self-modulated laser wakefield accelerator. The experiment was performed at the Jupiter Laser Facility, LLNL, by focusing the Titan short pulse beam (4-150 J, 1 ps) onto the edge of a Helium gas jet at electronic densities around 1019 cm-3. For the first time on this laser system, we used a long focal length optic, which produced a laser normalized potential a0 in the range 1-3. Under these conditions, electrons are accelerated by the plasma wave created in the wake of the light pulse. As a result, intense Raman satellites, which measured shifts depend on the electron plasma density, were observed on the laser spectrum transmitted through the target. Electrons with energies up to 200 MeV, as well as Betatron x-rays with critical energies around 20 keV, were measured. OSIRIS 2D PIC simulations confirm that the electrons gain energy both from the plasma wave and from their interaction with the laser field.

10234-2, Session 1

Investigation of electron dynamics in a ionization-injection laser-wakefield accelerator via betatron radiation

Alexander Koehler, Jurjen P. Couperus, Omid Zarini, Richard Pausch, Jakob M. Krämer, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany) and TU Dresden (Germany); Alexander Debus, Michael Bussmann, Arie Irman, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Ulrich Schramm, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany) and TU Dresden (Germany)

The injection process of electrons into the plasma cavity in laser-wakefield accelerators is a nonlinear process that strongly influences the property of the accelerated electrons. During the acceleration electrons perform transverse (betatron) oscillations around the axis. This results in the emission of hard x-ray radiation (betatron radiation) whose characteristics depend directly on the dynamic of the accelerated electrons. Thus, betatron radiation can be utilized as a powerful diagnostic tool to investigate the acceleration process inside the wakefield. Here we describe our recent LWFA experiments deploying ionization induced injection technique carried out with the Draco Ti:Sapphire laser. We focused 30 fs short pulses down to a FWHM spot size of 19 ?m resulting in a normalized vacuum laser intensity a0 = 3.3 on a gas target. The target, which was a supersonic gas jet, provided a flat plasma profile of 3mm length. By varying the plasma density from 2x10^18 cm^-3 to 5x10^18 cm^-3 and the laser pulse energy from 1.6 J to 3.4 J we were able to tune the electron bunch and betatron parameters. Electron spectra were obtained by acquiring an energy resolved and charge calibrated electron profile after detection from the beam axis by a permanent magnetic dipole. Simultaneously, a back-illuminated and deep-depleted CCD placed on axis recorded the emitted x-ray photons with energies up to 20keV. Equipped with an 2D spectroscopy technique based on single pixel absorption events, we reconstructed the corresponding energy resolved x-ray spectrum for every shot and deduced the betatron source size at the plasma exit. Combining the data of the electron and betatron spectrum, we compare the characteristics of the betatron spectra for different electron bunches. In our experiments we recorded a total number of 25x10^4 photons per shot within a divergence angle of 1 mrad and betatron radii in the order of 1 ?m. Finally, we compare our results with simulated spectra from the parallel classical radiation calculator Clara2 that is based on the Liénard-Wiechert potentials.

10234-3, Session 1

Generation of stable and polarized x-rays for application to femtosecond spectroscopy

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Betatron radiation from laser-plasma accelerators reproduces the principle of a synchrotron on a millimeter scale, but featuring femtosecond duration. Here we present the outcome of our latest developments, which now allow us to produce stable and polarized X-ray bursts. Moreover, the X-ray polarization can simply be adjusted by tuning the polarization of the laser driving the process. The excellent stability of the source is expressed in terms of pointing, flux, transverse distribution and critical energy of the spectrum. These combined features make our betatron source particularly suitable for applications in ultrafast X-ray science.

In this presentation we will describe the generation process, relying on the ionization injection scheme for laser-plasma acceleration. We will show experimental measurements, numerical results and first applications in time-resolved spectroscopy.

10234-4, Session 1

Experimental measurements of x-ray radiation due to betatron oscillations in a laser wakefield accelerator

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Betatron radiation has been extensively investigated in recent years because it is a promising new source of brilliant radiation from accelerators which are much more compact than conventional sources, such as synchrotrons. Laser driven radiation sources are of particular interest because of their natural synchronisation with the laser driver, and the possibility of obtaining ultra-short (attosecond to femtosecond) duration pulses, which are essential for reaching the unprecedented temporal resolutions required to follow electronic and molecular motion on their intrinsic time scales. Electrons injected with non-zero transverse momenta into the laser-driven plasma bubble begin to oscillate while they accelerate. These betatron oscillations result in ultra-short pulses of undulator or wiggler-like x-ray emission, which is comparable with the electron bunch duration. The radiation is emitted with a synchrotron spectrum with divergence of tens of milliradians that depends upon the Lorentz factor of the electrons. It is also nearly fully transversely polarised, similar to synchrotron radiation. Here we present experimental measurements of betatron radiation over a broad spectral range, recorded on the ALPHA-X beamline. We observe broad synchrotron spectra peaking at 3 and 20 keV, and extending from the vacuum ultraviolet to hard x-rays. We present measurements of the transverse coherence of the betatron radiation, which show that the radiation has a high transverse coherence, which is consistent the micron dimension source size.

10234-5, Session 1

Spatio-temporal description of the ion channel free-electron laser

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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 spatial period of transverse oscillations: In the former it is fixed by the undulator period, whereas in the latter it depends on the betatron amplitude, which therefore has to be treated as variable.

Even so, the resulting equations for the ICL are formally similar to those for the FEL with space charge taken into account. While we have shown previously how the well-developed formalism for the FEL can be applied to describe the ICL in the steady-state[1], we demonstrate here how it can be adapted to include propagation effects in a spatio-temporal description of the ICL.

[1] B. Ersfeld et al., New Journal of Physics 16 (9), 093025 (2014)

10234-6, Session 2

An ultrahigh gain amplifier based on Raman amplification in plasma

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The increasing demand for high laser powers is placing huge demands on current laser technology. This is now reaching a limit, and to realise the existing new areas of research promised at high intensities, new cost-effective and technically feasible ways of scaling up the laser power will be required. Plasma-based laser amplifiers may represent the required breakthrough to reach powers of tens of petawatt to exawatt, because of the fundamental advantage that amplification and compression can be realised simultaneously in a plasma medium, which is also robust and resistant to damage, unlike conventional amplifying media. Raman amplification is a promising method, where a long pump pulse transfers energy to a lower frequency, short duration counter-propagating seed pulse through resonant excitation of a plasma wave that creates a transient plasma echelon that backscatters the pump into the probe. Here we present the results of an experimental campaign conducted at the Central Laser Facility. Pump pulses with energies up to 100 J have been used to amplify sub-nanojoule seed pulses to near-joule level. An unprecedented gain of eight orders of magnitude, with a gain coefficient of 180 cm?1 has been measured, which exceeds high-power solid-state amplifying media by orders of magnitude. High gain leads to strong competing amplification from noise, which reaches similar levels to the amplified seed. The observation of 640 Jsr?1 directly backscattered from noise, implies potential overall efficiencies greater than 10%.

10234-7, Session 2

Redshift and harmonic radiation of nonlinear Laser-Thomson scattered X-rays

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Thomson scattering of intense laser pulses from relativistic electrons not only allows for the generation of bright x-ray pulses but also serves as a laboratory for strong field physics and nonlinear interactions. We present high resolution angle and energy resolved characterization of laser-Thomson scattered X-rays generated by colliding picosecond electron bunches from the superconducting ELBE linear accelerator with counter-propagating laser pulses from the 150 TW DRACO Ti:Sapphire laser system.

The measurements quantify the influence of the two major interaction parameters, namely laser intensity and electron beam emittance, on the spectral bandwidth of the scattered photons. The experimental range of normalized laser intensities (a0 from 0.15 to 1.7) covers the transition region from the linear to the nonlinear regime of the Thomson scattering interaction. In this parameter scan, we record and spectrally resolve the increasing redshift and broadening of the fundamental of the radiation, the rise of hamonics as well as the gain in total photon flux.

In the second study, we vary the interaction geometry, which allows for selecting only parts of the electron bunch to interact with the laser. By this means, we control the ensemble of interaction angles which is measured by the effective emittance of the electron beam. The bandwidth of the Thomson spectrum increases with the effective emittance, which can be used as a tuning knob for shaping the Thomson spectrum.

Numerical simulations of both studies performed with the classical radiation solver CLARA show good agreement, benchmarking this code with the experiments.

10234-8, Session 2

Scaling EUV and X-ray Thomson sources to optical free-electron laser operation with traveling-wave Thomson scattering

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Traveling-Wave Thomson-Scattering (TWTS) allows for the realization of optical free-electron lasers (OFELs) from the interaction of short, high-power laser pulses with brilliant relativistic electron bunches. The laser field provides the optical undulator which is traversed by the electrons. In order to achieve coherent amplification of radiation through electron microbunching the interaction between electrons and laser must be maintained over hundreds to thousands of undulator periods. Traveling-Wave Thomson-Scattering is the only scattering geometry so far allowing for the realization of optical undulators of this length which is at the same time scalable from extreme ultraviolet to X-ray photon energies. TWTS is also applicable for the realization of incoherent high peak brightness hard X-ray to gamma-ray sources which can provide orders of magnitude higher photon output than classic head-on Thomson sources.

In contrast to head-on Thomson sources TWTS employs a side-scattering geometry where laser and electron propagation direction of motion enclose an angle. Tilting the laser pulse front with respect to the wave front by half of this interaction angle optimizes electron and laser pulse overlap. In the side-scattering geometry the tilt of the pulse-front compensates the spatial offset between electrons and laser pulse-front which would be present otherwise for an electron bunch far from the interaction point where it overlaps with the laser pulse center. Thus the laser pulse-front tilt ensures continuous overlap between laser pulse and electrons while these traverse the laser pulse cross-sectional area. This allows to control the interaction distance in TWTS by the laser pulse width rather than laser pulse duration as is the case for head-on Thomson scattering. Utilizing petawatt class laser pulses with millimeter to centimeter scale width allows for the realization of compact optical undulators with thousands of periods.

When laser pulses for TWTS are prepared, care has to be taken of laser dispersion. Especially for scenarios featuring interaction angles of several ten to over one hundred degree the angular dispersion originating from laser pulse-front tilt can significantly prolong the pulse duration during the interaction which leads to a decrease in optical undulator amplitude and eventually terminates the interaction long before the target interaction distance is reached. In the talk it is shown how a pair of two gratings can be used to first generate the pulse-front tilt and second control and compensate dispersion during the interaction by utilizing the plane of optimum compression. Furthermore an experimental setup strategy is presented allowing for an interaction outside the laser pulse focus. This is a necessity for TWTS OFELs requiring focusing to reach optical undulator strengths on the order of unity since the centimeter scale laser pulse width at the interaction point result in turn in Rayleigh lengths on the order of one hundred meter and thus in laser focusing distances of several hundred meter. The talk shows how an out-of-focus interaction geometry utilizing strong focusing of the incident laser pulse needs to be designed in order to regain compactness by reducing the focusing distance by one to two orders of magnitude.

10234-9, Session 3

A new method to obtain narrowband emission from a broadband current using increased impedance of plasma-like media

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In conventional radiation sources, narrowband radiation emission can be obtained by narrowband current oscillation. Usually the spectrum of the oscillating current is made narrow by a large or complicated structure for wave-particle interaction. One good example is the beam-undulator system. In this presentation, we introduce a new method to obtain a radiation emission with a well-collimated frequency without changing the broadband nature of a given current source. The method is based on our recent discovery of the new physical properties of the cut-off phenomenon, which broadly exists in general plasma-like media, such as plasma, waveguide, or photonic crystal, etc. A common feature of these media is the Bohm-Gross dispersion relation, which has a frequency condition to make the wavenumber zero. In the zero-wavenumber state, an electromagnetic wave cannot propagate through the medium, but instead, is reflected (i.e. cut-off). In regular steady-state analysis, the cut-off condition is characterized by infinite radiation impedance. An interesting question here is what would happen to the radiation power, if a non-zero current oscillating with the cut-off frequency were enforced in a medium (a current source, in contrast with the regular voltage source). A regular steady-state analysis for this situation leads to infinite power of radiation from Ohm's law. We could solve such a paradoxical situation by analyzing the non-steady-state system; we found that the system can be described by a time-dependent Schroedinger equation with an external driving term. The solution of this equation shows a temporally growing electromagnetic field. When this concept is extended to a generally broadband current source, the spectral density at the cut-off frequency can be selectively enhanced (selectively enhanced emission, SEE). Hence a general broadband radiation source can be easily converted to a narrowband source by enclosing the system with a plasma-like medium. The current source seems to exist in many radiation systems with a low driver-to-emission efficiency. When the current is determined predominantly by the driver (for examples, laser pulses), while the feedback from the emitted field is weak, such current can be considered as a quasi-current source, We present a few examples (mostly from PIC simulations) to demonstrate the SEE; two-color-driven THz system enclosed by a tapered waveguide, THz emission from a magnetized plasma, and re-interpretation of experimental data. Those examples show that quasi-current source can be found in practical systems, and the SEE mechanism works.

10234-10, Session 3

High-power terahertz radiation from laser-produced plasmas

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The interaction of ultrashort intense laser pulses with plasmas either at gas or solid densities can produce not only X-ray radiation, but also broadband terahertz (THz) radiation with the highest peak power. There are several mechanisms responsible for such THz radiation, depending upon the laser intensity and target parameters. Recent progresses both in theoretical and experimental studies on this topic will be presented. In the interaction of intense lasers with a solid target, it is shown that the large flux of hot electrons with charge of a few nC per pulse can lead to THz radiation via coherent transition both in the front and at the rear

side of the solid target [1]. Terahertz field strength as high as sub GeV/cm is illustrated in numerical simulation [2,3]. When a large preplasma is formed in front of a solid target, it is shown that THz radiation can be found at the front side of the target produced via linear mode conversion from electron plasma wave excitation [4,5], where the plasma waves are excited either due to stimulated Raman backscattering or self-modulated laser wakefield excitation when the driving laser has relatively long duration. With gas targets, the two-color laser scheme for THz radiation due to field ionization currents has been investigated for a wide range laser and gas parameters, including the laser wavelength, laser intensity, pulse duration, relative phase of the two lasers, and gas species [6,7,8], as well as external DC magnetic fields [9,10]. It is shown that a preformed plasma wave such as excited by a laser wakefield can be used to modulate a laser pulse efficiently, forming an extreme broadband comb-like spectrum [11]. The comb tooth spacing is simply equal to the electron plasma frequency, which is typically in the terahertz range. With such modulated lasers, strong THz radiation with narrow bandwidth may be produced via optical rectification in nonlinear crystals.

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10234-11, Session 4

Plasma-based wakefield acceleration in strong fields

David A. Burton, Lancaster Univ. (United Kingdom)

Recent theoretical results pertaining to the energy gain of a particle in a plasma wakefield are discussed. The focus of the talk will be on the implications of couplings that arise in modern theories of dark matter. We will present a recent analysis [1] of particle acceleration within the semi-classical field theory of a relativistic plasma wave including quantum vacuum effects and axion-like particles.

[1] DAB, A Noble, TJ Walton, J. Phys. A: Math. Theor. 49 (2016) 385501.

10234-12, Session 4

Modelling electron and photon dynamics in intense laser pulses

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The next generation of high-power laser facilities, spearheaded by the Extreme Light Infrastructure (ELI), will produce electromagnetic fields of unprecedented intensities, in which new physical phenomena will become experimentally significant for the first time. It is vital for the successful planning and analysis of experiments at such facilities that the dynamics of charged particles and their radiation is properly understood.

Compton scattering from the collision of a high energy electron beam with an intense laser pulse is a promising source of bright x-rays. However, the strong dependence of the quality of the resultant radiation on the beam properties means it is essential to understand how these properties evolve as the electrons propagate through the laser pulse. While the behaviour of electrons in relatively low intensities is well established, in the extreme conditions available for example at the Nuclear Physics pillar of ELI, a number of new effects will qualitatively change the field-particle interactions. Prominent among these is the intricate interplay of quantum effects and radiation reaction.

A number of approaches exist for modelling quantum radiation reaction in ultra-intense fields, with varying degrees of completeness and rigour balanced against efficiency and ease of use. While one would ideally use the most efficient method that captures all the relevant physics, it is rarely obvious in a given context which complexities can be safely ignored. Moreover, different approaches may be more appropriate for different aspects of a single problem. We investigate the consequences of some of these approaches, and assess their suitability for modelling physics in the most intense fields.

10234-13, Session 4

Electron beam cooling in intense focussed laser pulses

Samuel R. Yoffe, Adam Noble, Alexander J. Macleod, Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

The development of high-power laser technology will allow investigation of qualitatively new physical regimes for the first time. Next-generation facilities (such as the Extreme Light Infrastructure) are due to become operational in the near future, for which it is essential to understand how laser--matter interactions behave at such high intensities. Two important aspects of the problem will be radiation reaction and quantum effects.

Radiation reaction describes the self-consistent emission of radiation by an accelerating charge. It causes an electron beam to undergo a reduction in its relative energy spread (known as beam cooling) as it interacts with a counter-propagating laser pulse, with classical theories overestimating the effect as the system becomes more quantum in nature. Semi-classical extensions and stochastic models for the photon emission have been developed in an attempt to address this and help design experiments to measure radiation reaction.

However, one shortcoming of many previous treatments is the assumption of planewave laser pulses which, unlike those used experimentally, do not exhibit transverse field structure. As such, particles cannot be kicked out of the pulse; instead, they artificially remain in the field and are forced to continue to radiate energy. In a planewave, electrons experience the same field, regarless of where they enter the pulse. Whereas, with the inclusion of transverse field structure, electron properties will depend greatly on when and where they radiate, with electrons ejected from the pulse at different locations. We study the effect caused by transverse structure on the distribution of electron bunches in strong fields and the radiation they produce.

10234-14, Session 4

On the momentum of light and the quantum vacuum

Alexander J Macleod, Adam Noble, Dino A Jaroszynski, University of Strathclyde (United Kingdom)

Electrodynamics is one of the most successful scientific theories ever produced. With the development of quantum mechanics we have gained significant further insight into the nature of light at the most fundamental level. Despite this progress, a long-standing controversy on the momentum of light in a medium still remains unresolved. Two rival expressions for the momentum, differing by the square of the refractive index, have each received compelling theoretical and experimental support over the century since originally proposed by Minkowski and Abraham.

Recent work has suggested that the discrepancy between the two descriptions lies in the different partitions between light and medium of the total energy-momentum tensor used for the light-medium system. While this idea is promising, the difficulty of accurately describing the material component of the energy-momentum tensor for realistic media makes it difficult to explicitly perform this separation in practice.

Here, we approach the problem from the perspective of nonlinear electrodynamics. A strong background field can cause free space to behave like a non-trivial medium because of the presence of quantum vacuum fluctuations. One result of this is that photons travelling through the field are subject to an effective refractive index, similar to those found in the low energy limit of string theory. Since we know the exact form of the electromagnetic energy-momentum tensor, we can avoid the requirement to describe the material medium and its response to the photons. Using this all-optical set-up, we analyse the momentum of light propagating through a constant magnetic field, and shed some light on the Abraham-Minkowski controversy. We also discuss some implications of this work for the very strong fields found around neutron stars, or available at upcoming high power laser facilities such as the Extreme Light Infrastructure.

10234-15, Session 4

Observations on the ponderomotive force

David A. Burton, Lancaster Univ. (United Kingdom); Robert A. Cairns, Lancaster Univ. (United Kingdom); Bernhard Ersfeld, Adam Noble, Dino A. Jaroszynski, Sam Yoffe, Univ. of Strathclyde (United Kingdom)

The ponderomotive force is a familiar and widely used idea in plasma physics and particularly in the area of laser-plasma interactions. The familiar form for the force in a purely oscillatory field is readily obtained, but in a travelling wave the problem becomes more complicated. We consider the most basic problem of a particle moving in an electrostatic wave, coming from a region of zero field into a region of increasing wave intensity and being reflected. For this problem a formula for the ponderomotive force has been given, as a special case, by Bauer et al (Phys. Rev. Lett. 75, 4622, 1995). This is derived from an averaged Lagrangian technique, while for the same problem a ponderomotive potential has been obtained from Hamiltonian methods by Cary and Kaufman (Phys. Rev. Lett. 39, 402, 1977). These latter authors do not give an explicit formula for the force, but we show that it yields the same result as that given by Bauer et al. To test this analytic formula we compare its predictions with the results of an exact integration of the equation of motion, smoothed over the fast oscillations.

Up to a certain value of wavenumber we find excellent agreement between the exact and analytic results, but then we reach a value at which the analytic formula encounters a singularity while the exact solution remains well behaved. As the wavenumber is further increased we encounter a parameter range where the particle, after reflection, is initially accelerated in the outward direction but its velocity then falls as it moves down the intensity gradient. Such a change in the sign of the acceleration can be given by the Bauer et al formula, but we show that with this formula it is impossible for the acceleration to make the transition that we see. In fact, it can be seen that such a transition cannot be obtained from any Lagrangian with a quadratic dependence on the field amplitude. Either the acceleration is always down the intensity gradient, in the familiar way, or always up the intensity gradient. Finally, a further increase in wavenumber brings us to a regime where the particle's peak velocity reaches the wave phase velocity and it is given an abrupt kick to a higher velocity.

Our conclusion is that expressions in the literature for ponderomotive force and ponderomotive potential in a travelling wave have a limited range of validity and that there are parameter ranges in which no ponderomotive potential quadratic in the electric field amplitude can be valid when used in a Lagrangian. The familiar and longstanding problem of the ponderomotive force would thus seem to warrant further study in view of its relevance to such topics as Raman amplification, laboratory astrophysics and laser wakefield acceleration.

Conference 10235: EUV and X-ray Optics: Synergy between Laboratory and Space

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10235-1, Session 1

Lobster eye optics on suborbital rockets *(Invited Paper)*

James H. Tutt, The Univ. of Iowa (United States)

The sub-orbital flight of the WRX-R payload offers a unique opportunity to fly an instrument based around lobster eye optic modules and Timepix detectors. WRX-R, a re-flight of the OGRESS sub-orbital rocket, is a soft X-ray diffuse spectrometer with a large field-of-view that will be targeting the Vela supernova remnant. OGRESS was a two channel telescope, but due to limitations on the focal plane detector, only one telescope will be used on WRX-R. This opens up space on the optical bulkhead for the inclusion of this second instrument. The lobster eye instrument is best suited to the observation of point sources that are bright in the hard X-ray; therefore, its pointing has to be offset from the pointing of the main telescope to allow the neutron star at Vela's center to be observed. Through the flight of an offset lobster eye optic together with the rockets main payload, it will be possible to make dual observations of Vela during a single rocket flight, increasing the scientific yield of WRX-R.

10235-3, Session 1

Prototyping iridium coated mirrors for X-ray astronomy

Thorsten Döhring, Anne-Catherine Probst, Manfred Stollenwerk, Hochschule Aschaffenburg (Germany); Veronika Stehlíková, Adolf J. Inneman, Czech Technical Univ. in Prague (Czech Republic)

X-ray astronomy uses space-based telescopes to overcome the disturbing absorption of the earth atmosphere. The telescope mirrors are operating at grazing incidence angles and they are coated with thin metal films of high-Z materials to get sufficient reflectivity for the high-energy radiation to be observed. In addition the optical payload needs to be lightweighted for launcher mass constrains. Within the project JEUMICO, an acronym for "Joint European Mirror Competence", the Aschaffenburg University of Applied Sciences and the Czech Technical University in Prague started a cooperation to develop mirrors for X-ray telescopes. This bilateral project is jointly funded by the Bavarian State Ministry of Education, Science and the Arts and the Ministry of Education, Youth and Sports of the Czech Republic. The X-ray telescopes currently developed within this Bavarian-Czech project are of Lobster-Eye type optical design. The corresponding mirror segments use substrates of flat silicon wafers which are coated with thin iridium films, as this material is promising high reflectivity in the X-ray range of interest. The deposition of the iridium films on the mirror substrates is based on a magnetron sputtering process. Sputtering with different parameters, especially by variation of the argon gas pressure, leads to iridium films with different properties. In addition to investigations of the uncoated mirror substrates the thin films density, their crystalline structure, the achieved surface roughness and the resulting coating stress have been studied. Thereby the sputtering parameters are optimized in the context of the expected reflectivity of the coated X-ray mirrors. The obtained experimental results of the development process are presented within this paper. The produced prototype mirrors will be integrated into an X-ray telescope. In near future measurement of the mirror modules optical performance is planned at an X-ray test facility.

10235-4, Session 1

Study of lobster eye optics with iridium coated X-ray mirrors for a rocket experiment

Veronika Stehlíková, Martin Urban, Ondrej Nentvich, Adolf J. Inneman, Czech Technical Univ. in Prague (Czech Republic); Thorsten Döhring, Anne-Catherine Probst, Hochschule Aschaffenburg (Germany)

In the field of astronomical X-ray telescopes different types of optics based on grazing incidence mirrors can be used. This contribution describes the special layout of a lobster-eye optic in Schmidt's arrangement, which uses dual reflection to increase the collecting area. The individual mirrors of this wide-field telescope are made of flat silicon wafers coated with an iridium reflecting layer. As shown in corresponding simulations, iridium coatings have some advantages when compared to more common gold layers in this case. The iridium coating process for the X-ray mirrors is developed within a cooperation of the Aschaffenburg University of Applied Sciences and the Czech Technical University in Prague. Different mirror parameters essential for a proper function of the X-ray optics, like the surface micro-roughness and the flatness of mirrors, as well as the problematics of a good adhesion quality of the coatings was studied. After integration of the individual mirrors into the final lobster-eye optics and a corresponding testing it is planned to fly the telescope in a recently proposed NASA rocket experiment.

10235-5, Session 1

Recent advances in reflective optics for EUV/X-ray sources at Thales SESO

Monique Ide, Thales SESO S.A.S. (France); Luca Peverini, ESRF - The European Synchrotron (France); Denis Fappani, Thales SESO S.A.S. (France)

Over more than 50th years Thales SESO represent a world leading designer and manufacturer of highend, optical components such as telescopes and satellite-based space observation optics operating over the entire spectral range from infrared to x-ray wavelengths. Since early 90th we are actively working in the EUV, Soft-X-ray and hard X-ray spectral range, by developing new equipment and introducing metrology innovations and brand new patented products such as bender and bimorphs mirrors (1st and 2nd generation). In particular a set of customized solution (integrated system) for imaging and spectroscopy have been developed basing on the original Wolter and Kirckpatrick-Baez design.

Few example of reflective optics behaving both, as collimator, focusing and imaging device will be discussed through the talk. A set of innovating solutions to realize fixed curvature optics and dynamically bended device will be detailed to illustrate the flexibility and performances of these products. The latter points are particularly important for high power sources such as XFEL and synchrotrons source upgrades presently in progress.

10235-36, Session 1

X-ray Lobster Eye all-sky monitor for rocket experiment

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(Czech Republic); Tomá? Bá?a, Veronika Stehlíková, Ondrej Nentvich, Martin Urban, Czech Technical Univ. in Prague (Czech Republic); Randall L. McEntaffer, James H. Tutt, The Univ. of Iowa (United States); Timothy J. Schulz, Pennsylvania State Univ. (United States)

The paper presents the Lobster Eye (LE) X-ray telescope developed for the Water Recovery X-ray Rocket (WRX-R) experiment. The primary payload of rocket experiment is the soft X-ray spectroscope and it is prepared by the Pennsylvania State University (PSU), USA. The Czech team participates by hard LE X-ray telescope as a secondary payload. The astrophysical objective of the rocket experiment is the Vela Supernova with size about 8deg x 8deg. In the center of the nebula is a neutron star with a strong magnetic field, roughly the mass of the Sun and a diameter of about 20 kilometers forming the Vela pulsar.

The primary objective of WRX-R is the spectrum measurement of the upper part of the nebula in soft X-ray and FOV of 3.25deg x 3.25deg. The secondary objective (hard LE X-ray telescope) is neutron star observation. The hard LE telescope consists of two X-ray telescopes with the Timepix detector. First telescope uses 2D LE Schmidt optics with focal length over 1m and 4 Timepix detectors (2x2 matrix). The telescope FOV is 1.5deg x 1.5deg with spectral range from 3 keV to 60 keV.

Second telescope uses 1D LE Schmidt optics with focal length of 25 cm and one Timepix detector. The telescope is done as a wide field with FOV 4.5deg x 3.5deg and spectral range from 3 keV to 40 keV.

The rocket experiment serves as the technology demonstration mission for the payloads. The LE X-ray telescopes can be in future used as an all?sky monitor/surveys. The astrophysical observation can cover the hard X-ray time-domain astrophysical sources observation, the GRBs surveying or the exploring of the gravitational wave sources.

10235-6, Session 2

The future of high resolution X-ray optics for astronomy *(Invited Paper)*

Paul Gorenstein, Harvard-Smithsonian Ctr. for Astrophysics (United States)

Beginning with the Einstein Observatory in 1978, continuing with ROSAT in the 1990's and currently the Chandra X-Ray Observatory, high angular resolution focusing telescopes have been the premier X-ray astronomy instruments of their time. However, as they have acquired larger area and improved angular resolution they have become increasingly massive and expensive. The successor to Chandra planned for the late 2020's currently named "Lynx" will rely on active optics to allow the use of much lower mass segmented mirrors with the goal of gaining an order of magnitude larger area than Chandra with a lower ratio of mass to effective area and perhaps slightly better angular resolution than Chandra's 0.5 arc second half power diameter and/or over a somewhat larger field. The goals for Lynx are probably at the limit of what is possible with grazing incidence X-ray optics. Success in the development of higher angular resolution, lower mass telescopes will come at the expense of effective area. A diffractive-refractive pair consisting of a Fresnel zone plate and a diffractive lens that transmits rather than reflects X-rays is capable in theory of achieving mili arc second resolution with a much lower ratio of mass to effective area than the grazing incidence reflective Wolter optics. However, the focal lengths of this system are thousands of kilometers necessitating formation flying between one spacecraft hosting the optics and another hosting the detectors, most likely in a Sun-Earth L2 orbit. The trajectory of one of the two spacecraft can be in a true orbit but the other must be powered by an ion engine to maintain the alignment. The growing interest in deep space astronaut operations may allow the ion engines to be replaced when depleted.

10235-7, Session 2

Current developments and tests of small X-ray optical systems for space applications

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The presentation addresses the X-ray monitoring for astrophysical applications. A novel approach based on the use of 1D and 2D "Lobster eye" optics in combination with Timepix X-ray detector in the energy range 3 - 40 keV was further studied. Wide-field optical system of this type has not been used in space yet. Designed wide-field optical system combined with Timepix X-ray detector is described together with latest experimental results obtained during laboratory tests. Proposed project includes theoretical study and a functional sample of the Timepix X-ray detector with multifoil wide-field X-ray "Lobster eye" optics. Using optics to focus X-rays on a detector is the only solution in cases where intensity of impinging X-ray radiation is below the sensitivity of the detector, e.g. while monitoring astrophysical objects in space, or phenomena in the Earth's atmosphere. The optical system is considered to be used in a student rocket experiment.

10235-8, Session 2

Application of biomimetics in X-ray optics

René Hudec, Astronomical Institute of the ASCR, v.v.i., The Czech Academy of Sciences (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Katerina Remisova, Astronomical Institute of the ASCR, v.v.i., The Czech Academy of Sciences (Czech Republic) and Charles Univ. in Prague (Czech Republic)

The principles of biomimetics were succesfully applied in X ray optics in the past and recently, e.g. in Lobster-Eye optical systems. However, the recent growing knowledge of sea vision, especially of peculiar mirror eyes of scallops, crustaceans, and deep sea fishes, makes possible to consider other such applications.

Perhaps the most important new discovery is deep sea fish Rhynchohyalus natalensis with mirror eyes based on very large numbers of very small mirrors developed from the choroidal argentea wi th crystals orientated almost parallel to the mirror's surface. This arrangement may even include principles of active optics.

We report on ongoing study with focuss on understanding of very specific mirror eyes of sea animals and how they may help us to design and develop special optics for scientific applications. We study the ways these mirror eyes work, what are the advantages of these peculiar eye arrangements, and whether these optics can be used in advanced devices, e. g. X ray optics. We will briefly present and discuss the preliminary results.

10235-9, Session 2

Optimization of microroughness of replicated X-ray optics

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We report on our work of minimising the microroughness of replicated grazing incidence X-ray optics. Ion beam and RF sputter cleaning was used as surface treatment and we compare its effects in the article. Vacuum deposition of smoothing layers was also used for minimising the microroughness. The surfaces were measured by atomic force microscopy and X- ray reflectometry. Mircoroughness less than 0,5 nm RMS and Ra was achieved.

10235-10, Session 2

Joint observations of solar corona in space projects ARCA and KORTES

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ARCA and KORTES are two upcoming Russian solar space missions in extreme ultraviolet and X-ray spectral wavebands. KORTES will have EUV and soft X-ray telescopes, EUV spectroheliographs and an X-ray spectrometer onboard. ARCA will carry only EUV telescopes, but their spatial resolution is expected to be high (about 0.1 arcsec. which corresponds to about 100 km on the surface of the Sun).

ARCA is a new Russian solar mission intended to take high-resolution images of the sun in the extreme ultraviolet wavelengths. ARCA will be equipped with two high-resolution Ritchey-Chretien telescopes designed to collect images of the Sun with approximately 150 km spatial resolution in the field of view of about 10??10?. These two high-resolution EUV telescopes will play a role of a “magnifying glass” and the section of the Sun which requires current observation will be adjustable. One full-disc EUV telescope with moderate spatial resolution will also be mounted onboard the satellite to afford full-Sun observations at a time.

The scientific results of the ARCA mission may have a significant impact on the theory of coronal heating and may help to clarify the physics of small scale solar structures and phenomena including oscillations of fine coronal structures as well as the physics of micro- and nanoflares.

KORTES is a Sun-oriented mission designed for the Russian segment of International Space Station (ISS). Since the ISS has a nadir orientation, the KORTES will be mounted on a special pointing platform that will track the position of the Sun throughout the whole orbit of ISS.

KORTES consists of several imaging and spectroscopic instruments that will observe the solar corona in a number of wavebands, covering EUV and X-ray ranges:

- 3 EUV telescopes (195, 304 and 584 Å channels) with full-Sun field of view
- 2 EUV imaging spectroheliographs (170–210 and 280–330 Å wavebands)
- an X-ray telescope with moderate dispersion (8.42 Å Mg XII channel) with full-Sun field of view
- an X-ray complex spectrometer Solpex (1–15 keV energy range with polarization metering)

The surveillance strategy of KORTES will allow for a wide range of observations including simultaneous imaging and spectroscopic measurements and hence KORTES data would represent an important tool for investigation of structure and dynamics of coronal plasma as well as temperature and density diagnostics.

The scientific objectives of the mission include investigation of the fundamental physical processes occurring in the solar corona, such as the generation of solar flares, the formation and evolution coronal mass ejections, etc. Together with other solar missions (ARCA, STEREO, HINODE, SDO) KORTES will bring a new light to understanding of physics of solar corona.

To reach the proposed scientific goals the scientific instruments for both ARCA and KORTES will call for the latest achievements in the fabrication of EUV multilayer mirrors and thin-film spectral filters, modeling of optical layouts and behavior of diffraction-limited optical schemes, and the latest image registration techniques (including backside-illuminated EUV/SXR-oriented CCD-matrices).

10235-11, Session 2

Deformation-free rim for the primary mirror of telescope having sub-second resolution

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10235-24, Session PS

Data processing from lobster eye type optics

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Nowadays are commonly used Kirkpatrick-Baez or Wolter type optics in X-Ray spectrum. This system uses two reflections and at higher energies these systems are not so much efficient but have very good optical resolution. Here is another type of optics - Lobster Eye, which is using only one reflection for focusing rays. The Lobster Eye optics has better efficiency at higher energies compared to Kirkpatrick-Baez or Wolter type optics. This paper describes advantages one dimensional and two dimensional Schmidt’s arrangement of Lobster Eye optics and its data processing - find out quantity of sources, their direction and magnitude. Two dimensional optics are good for simple detection of quantity of sources, but it is necessary to expose for longer time because has much more lower transmissivity compared one dimensional optics. For lower magnitudes of sources is better to use two one dimensional optics. In this case is necessary additional image processing to get two dimensional image. Disadvantageous in additional processing is the result contains fake sources when more sources is taken. One of possible solution how to get number of sources is to compute magnitude of each line and determine pairs of vertical and horizontal lines, which is required to separate and then mathematically multiply to get right results.

This implementation brings advantages of 2D optics without losses of transmissivity.

10235-25, Session PS

New design of spectrometer for X-ray astrophysics

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In the field of X-ray detection for Astrophysics are mainly two objectives; to create the 2D images as a result of sensing radiation by detectors consisting of a pixels matrix. The second is a spectral analysis of the incident radiation. For spectral analysis, the basis is usually the principle of diffraction. This paper describes the new design of X-ray spectrometer based on Timepix detector with optics positioned in front of it. The advantage of this setup is an ability to get the image and spectrum from the same devices. With other modifications is possible to shift detection threshold into areas of soft X-ray radiation.

10235-26, Session PS

Development and demonstration of a water-window soft X-ray microscope using a Z-pinching capillary discharge source

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The development and demonstration of a soft X-ray (SXR) microscope, based on a Z-pinching capillary discharge source has been realized. The Z-pinching plasma acts as a source of SXR radiation. A ceramic capacitor bank is pulsed charged up to 80 kV, and discharged through a pre- ionized nitrogen filled ceramic capillary. The discharge current has an amplitude of ~25 kA. Working within the water-window spectral region (? = 2.88 nm), corresponding to the 1s2-1s2p quantum transition of helium-like nitrogen (N5+), the microscope has a potential in exploiting the natural contrast existing between the K-absorption edges of carbon and oxygen as the main constituents of biological materials, and hence imaging them with high spatial resolution. The SXR microscope uses the grazing incidence ellipsoidal condenser mirror for the illumination, and the Fresnel zone plate optics for the imaging of samples onto a BI-CCD camera. The half- pitch spatial resolution of 100 nm [1] was achieved, as demonstrated by the knife-edge test. In order to enhance the photon-flux at the sample plane, a new scheme for focusing the radiation, from multiple capillary sources has been investigated. Details about the source, and the construction of the microscope are presented and discussed.

[1] Nawaz, M. F., et al. "Table-top water-window soft X-ray microscope using a Z-pinching capillary discharge source." Journal of Instrumentation 11.07 (2016): P07002

10235-27, Session PS

Diffraction/refraction optics for hard x-ray radiation: from 10 keV to 100 keV

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At the present time reflection zone plates working on total external reflection (focusing as well as energy-dispersive elements for 20 eV to 12 keV energy range) are starting to get more attention due to advanced surface polishing technology and possibilities of creating layouts in resist layer by either e-beamlithography or photolithography. Feasibility of finest design features as small as 40 nm (e-beam lithography) and total layout area as large as 2000 mm2 and more allow one to create diffractive structures for a wide variety of applications: time-resolved experiments, scan probe experiments (micro fluorescence analysis) [1] , etc. For 10 keV – 50 keV energy range it is possible to use diffractive structures based on silicon or germanium crystals with high Muller indexes. It is clear that from 20 keV to 100 keV refractive optics must be used. In 1996 B. Lengeler suggested to use such elements for focusing and collimating the "hard" X-ray radiation [2]. The use of refractive optical elements for converting the hard x-ray radiation and neutron radiation is presented in [3].

We propose to discuss the use cases reflection zone plates working on total external reflection as well as working on Bragg reflection in energy range 6 keV – 50 keV.

In this work we would like to present a monochromator for a wide energy range. This part of the report is devoted to design, optimization and simulation of compound refractive optics for spectral analysis of "point" hard X-ray (30-100keV) source. Two elements we would like to focus on are simple compound prism and compound refractive off-axis lens.

It is shown that such devices have: small element of 20mm in length, compact spectrometer setup (of about 2 meters long). The devices provide: angle resolution 10-5rad of source radiation, spectral resolution 300eV at 30keV and 2000eV at 100keV, efficiency 10-4 (10-4 part of x-ray quanta will be used for spectrum analysis).

1. Karsten Holldack, Johannes Bahrdt, Andreas Balzer, Uwe Bovensiepen, Maria Brzhezinskaya, Alexei Erko, Andrea Eschenlohr, Rolf Follath, Alexander Firsov, Winfried Frentrup, Loiic Le Guyader, Torsten Kachel, Peter Kuske, Rolf Mitzner, Roland Muller, Niko Pontius, Torsten Quast, Ilie Radu, Jan-Simon Schmidt, Christian Schußler-Langeheine, Mike Sperling, Christian Stamm, Christoph Trabantd, and Alexander Föhlisch, FemtoSpeX: a versatile optical pump–soft X-ray probe facility with 100 fs X-ray pulses of variable polarization, J. Synchrotron Rad. (2014). 21

2. A. Snigirev, V.Kohn, I. Snigireva, B. Lengeler, A compound refractive lens for focusing high-energy X-rays, Nature 384, 49 - 51 (07 November 1996).

3. W. Jark, F. Perennes, M. Matteucci, and L. De Caro, CLESSIDRA: Focusing Hard X-rays Efficiently with Small Prism Arrays, Modern Developments in X-Ray and Neutron Optics, A. Erko, M. Idir, T. Krist, A. G. Michette (Eds.) Springer Series in OPTICAL SCIENCES, p331 – 352.

10235-28, Session PS

Development of laboratory metrology for X-ray refractive lenses

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Refractive X-ray optics has been successfully used for focusing and imaging of high energy X-rays at synchrotron radiation sources for the last 20 years [1]. Despite the successful development of refractive optics for X-ray nano-focusing [2] and high-resolution X-ray microscopy [3] the diffraction resolution limit for compound refractive lenses (CRL) has not been achieved. It is known that imaging properties of the CRL depend on the refractive properties of the used lens materials, and on the accuracy of the manufacturing the lens optical surface (figure errors) [4]. To improve the lens surface quality, dedicated metrological methods to measure geometric characteristics of the CRL parabolic profile are required.

In this work aluminum, beryllium refractive lenses with a parabolic profile (small radii of curvature R = 50 mm ÷ 1000) obtained by pressing technique and also punching tool with a parabolic profile used in the manufacture of refractive lenses were studied using laboratory X-ray sources, profilometry, optical and electron microscopy.

The software developed by us was used to analyze the acquired images and the profile points of refractive lens profile in order to determine the values of lenses geometrical characteristics: the radius of curvature of the profile shape, the width of aperture and the distance between refractive surfaces. The software is based on an algorithm which analyzes the images, receives profile point and approximates these data with the second-order curve by the least-squares fitting using the regression analysis. Application of the regression analysis allows to assess the adequacy of the proposed model for the geometrical description of the lens profile.

The work presents a comparison of different methods for metrological research of profiles of X-ray refractive lenses. Comprehensive laboratory metrological approaches allowing to control the quality of the lens profile and to make the input quality control of printing tools were proposed.

1. A. Snigirev, V. Kohn, I. Snigireva & B. Lengeler // Nature 384, 49 - 51 (07 November 1996).

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10235-29, Session PS

The influence of internal beryllium microstructure on the optical properties of compound refractive lenses

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In order to use the full potential of new coherent synchrotron radiation sources, the highest quality of X-ray optics is needed. Besides, it has to be resilient to extreme thermal and radiation loading while preserving beam coherence. Compound refractive lenses are a good candidate to achieve this goal.

This work presents the results of the influence of beryllium microstructure on the optical properties of compound refractive lenses in hard X-ray nanoprobe applications and coherent high-resolution transmission X-ray microscopy. The paper offers recommendations on beryllium refractive lenses and beryllium X-ray windows manufacturing processes by using different beryllium grades for diverse applications of hard X-ray optics.

10235-30, Session PS

High-resolution X-ray computed tomography as a diagnostic method of compound refractive lenses

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Compound refractive lenses with parabolic profile (CRL) are amongst the most advanced optical components at the synchrotrons worldwide for high-resolution X-ray microscopy and focusing applications. The assessment of impact of the internal structure of the lens material on the lens optical properties is required for further improvement of the CRL manufacturing technology. At the same time, actual task is the inspection of the defects in the CRL workpiece and analysis of its geometric properties: the lens profile and coaxiality of the refracting surface.

At this work, we present results of characterization of refractive X-ray lenses using the laboratory high resolution X-ray computed tomography (HRXCT). This technique allows to investigate the internal structure of materials, imperfections and geometrical properties in a three-dimensional voxel model and to obtain any cross-sections of the samples for further analysis.

HRXCT was performed using the X-ray inspection system Y. Cheetah designed for generating high-quality X-ray images with the 1 μm resolution. By using a Fein Focus tube with effective spot size less than 2 microns a high resolution was provided which was sufficient to examine imperfections of few microns in size. Lenses made of high-purity aluminum with the parabola apex radii of 50 μm were studied.

This work shows that the HRXCT inspection could effectively evaluate the main characteristics such as the quality of the materials and the geometric parameters of CRL, ensuring development of the lens manufacturing technology from a variety of radiolucent materials.

10235-31, Session PS

Pd/Y multilayer mirrors with a Mo barrier

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Although Pd/Y multilayer operating in the 8-12 nm wavelength range can reach high theoretical reflectivity of 65% at normal incidence, a serious intermixing of neighboring Pd and Y layers leads in an almost total disappearance of the interfaces inside the multilayers made by direct current magnetron sputtering, which make a dramatic reflectivity decrease. Based on grazing incidence X-ray reflectometry and reflectivity measurements, we demonstrate that the interfaces in Pd/Y multilayer structures can be improved by adding a small thickness of Mo as a barrier layer. The grazing incidence X-ray reflectivity as a function of the grazing angle for Y/Mo/Pd and Pd/Mo/Y multilayers show that the structure of Y/Mo/Pd multilayer is better than that of Pd/Mo/Y one. The reflectivity values around 11.5nm at normal incidence for Y/Mo/Pd, Pd/Mo/Y, and Mo/Y/Mo/Pd are limited and just a few percent. All the experiments reveal that Mo can be a barrier layer and just a little improve the quality of the structure of Pd/Y multilayer.

10235-32, Session PS

Development of lidar for remote sensing of the Martian surface

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More recently, Mars became the object of research is associated primarily with the development of techniques and technologies that allow a detailed way to explore the planet's surface. These studies are quite relevant, because humanity sees Mars as their new home. For potential terraforming key factor is the presence of water on the red planet. At the moment there are two ways to study the surface: contact and contactless.

To contact methods include rovers, delivered to the surface of Mars. Unfortunately rovers have fairly low speed, which greatly increases the time spent on research alone, even a small portion of the surface. Also cross-country rover is not high enough, it also affects the speed of research.

For contactless electronic methods include the latest telescopes based on Earth but telescopes do not provide accurate and detailed information, which in turn does not accelerate and simplify the study the planet's surface.

At this time, none of the existing methods of probing the surface of Mars is not able to look into the deep Martian crevices, which according to preliminary estimates and may be of Martian water reserves. Therefore, to solve this problem will require the machine, orbiting Mars, which will be used as a special rangefinder.

On the surface of the red planet water was found in two of its aggregate states, namely water vapor and ice. However, September 29, 2015, when the average Martian temperature rose to -23 degrees Celsius, supersensitive equipment was able to detect a watery suspension.

Detailed spectral analysis showed that the aqueous slurry contains impurities, the most striking is its components H2S and HCL. Therefore, as the indicator substances, it was decided to select H2O, H2S and HCL.

Given the structure of Mars atmosphere, namely the fact that it consists of CO2 (95%), Ar (1.6%), N2 (2.7%), O2 (0.13%) and CO (0.07%), and taking into account the range of atmospheric transmittance should that the best area for sensing a UV range.

As a method for remote sensing of the most effective is the Raman scattering method that allows to detect several substances indicators without complicating the structure of the device, in contrast to the method of differential absorption and scattering, as for the detection of substances it requires two power sources, thus to detect three substances required indicators I have enormous energy.

Taking the existing at this time «NOMAD», the best option would be to use the circuits of the monostatic lidar, which will minimize the size of the device, since the receiver is in the immediate vicinity of the source, and it reduces the costs associated with the development and maintenance of such a device. So take a monostatic lidar scheme for constructing the basis for the most suitable option.

The aim is to create a model of such a device, which in the future will lead to the development of a prototype that can find water on the red planet.

10235-33, Session PS

High-aperture monochromator-reflectometer and its usefulness for CCD calibration

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Here we report on a device which is useful for testing optical elements for upcoming solar space missions.

We have designed and assembled a laboratory monochromator-reflectometer for a wide range of applications in soft X-ray spectral range. Now we demonstrate its operability by means of a laboratory CCD calibration. We plan to use this CCD as a reference standard for future measurements. The distant goal is to employ a number of soft X-ray CCD matrices as the detectors in future space telescopes and spectroheliographs (KORTES and ARCA projects).

The monochromator-reflectometer consists of a set of replaceable Schwarzschild objectives, a light source, a goniometer and a calibrated detector. Now we have three sets of Schwarzschild objectives for different spectral wavelengths: 131 Å, 171 Å and 304 Å. Each objective comprises two periodic soft X-ray multilayer mirrors with identical multilayer structure, and the mirrors are responsible for monochromatization of the incident radiation.

As a source of light we use laser-driven plasma emerging under irradiation of a cylindrical steel target by nanosecond laser pulses (Nd:YAG, 0.5 J, 5 ns, 1064 nm). Then the Schwarzschild objective focuses the radiation into the center of the goniometer. Free-standing thin-film spectral filters also apply to diminish visible light coming through the optical system due to mirror reflections, and for a single narrow monochromatic spectral line to be present in the radiation propagated.

The goniometer has three degrees of freedom, which allows moving an optical element under study in horizontal and vertical directions (perpendicularly to the optical axis of the system) with additional rotation around a vertical axis.

There are two calibrated IRD silicon detectors used in the optical layout of the monochromator-reflectometer, which enables suitable CCD calibration procedure and permit mapping of the sensitivity values over the whole CCD aperture.

This is the reason why our first measurements secured by the monochromator-reflectometer were laboratory CCD-matrix calibration. Combined with results of our previous measurements of the CCD sensitivity in the 110-600 nm waveband, we have a deeper understanding of the CCD operation and of its effectivity in a wide spectral range.

The monochromator-reflectometer is suitable for testing such optical elements as diffraction gratings, soft X-ray multilayer mirrors, thin-film free-standing spectral filters, CCD-matrices and so on. We plan to use its capabilities for the upcoming soft X-ray solar space missions ARCA and KORTES.

10235-34, Session PS

Optical performances of aluminum based phase retarder in EUV and FUV range

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Aluminum has been known for a long time as competent material for quarter wave retarder in the FUV range with high reflectivity However, the serious problem of Al mirrors is the high oxidation reducing the reflectance of the aluminum in this region so that, multilayer thin film can be a good alternative to achieve phase retardation by reflection in this wavelength region. The other prevalent problem is the combination of Al with fluorides groups as MgF 2 where a serious drop of reflectivity is observed due to covering the absorption edge of fluoride compounds.

For that purpose, we designed a multilayer based on Aluminum combined with other materials to obtain a phase retarder by 900 working in a wider spectral range of FUV and EUV (121.6 - 91.2 nm) with high, matched reflectance for both S and P polarization, the planned design extends on a challenging spectral range covering the absorption edge of fluorides at 105 nm. The design approach can be used for any other spectral range of wavelengths in FUV and EUV where a selection of the working wavelength and optimization of the phase difference between s and p components will be obtained by changing the angle of incidence on the sample.

The reflective phase retarder of our multilayer mirror was deposited by the technique of electron beam evaporation. The thickness of the films was designed such that to obtain a Quarter Wave Retarder working at different FUV -EUV wavelengths and was characterized by profilometry. To fully control the properties of a propagating beam, knowledge, and control of the efficiency and phase introduced by the optical components upon reflection so that, the mirrors were characterized by combining the reflectivity with total electron yield signal at the synchrotron radiation in Trieste, Italy in energy range 14.5 to 8 eV. Another trend is measuring the phase difference at EUV reflectometer facility available in (LUXOR-CNR Padova, Italy) that uses a polarizer and an analyzer, which are rotated independently around the optical axis to retrieve the complete state of polarization of an electromagnetic wave.

10235-12, Session 3

Reflective optics for effective collection of X-ray and EUV radiation: use for creation of photoionized plasmas and detection of weak signals

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X-ray or extreme ultraviolet (EUV) space telescopes are equipped with different kinds of specialized reflective optical systems. The systems are prepared for imaging of astrophysical objects located at extremely long distances. In laboratory arrangements similar optical systems can be

utilized for X-ray/EUV imaging or formation of the X-ray/EUV radiation beams. The essential differences concern distances from radiation sources to the corresponding optical systems and intensities of the collected radiation. The distance to any astrophysical object can be regarded as infinity, distances in case of laboratory systems are short, of the order of meters or centimeters. Intensities of the collected radiation in laboratory systems are many orders of magnitude higher comparing to the astronomical telescopes.

In this work different kinds of reflective optical systems were used for creation and investigation of low temperature, photoionized plasmas. The plasmas were created in gases irradiated with a focused EUV or soft X-ray (SXR) beam from laser-plasma sources employing 10 Hz Nd:YAG laser systems (0.8 J/ 4 ns and 10 J/ 1-10 ns) or the PALS laser system (600 J/ 0.3 ns). EUV radiation created using the 0.8 J Nd:YAG laser was focused using a gold-plated grazing incidence ellipsoidal collector in the wavelength range ? = 9÷70 nm. The most intense emission was in the relatively narrow spectral region centred at ? = 11 ± 1 nm. In case of the 10 J Nd:YAG laser SXR/EUV radiation was focused using a gold-plated grazing incidence multifoil collector in the wavelength range ? = 5 ÷ 70 nm or the paraboloidal collector optimized for the wavelength range ? ≥ 1 nm. The most intense emission was in the 1 ÷ 15 nm spectral region. In case of the PALS system the paraboloidal collector was employed.

Different gases were injected into the vacuum chamber, perpendicularly to an optical axis of the irradiation system at the focal region, using an auxillary gas puff valve. Irradiation of the gases resulted in ionization and excitation of atoms/molecules. Spectra in SXR/EUV range were measured using a grazing incidence, flat-field spectrometer (McPherson Model 251), equipped with a 450 lines/mm toroidal grating or a home-made spectrograph based on the 5000l/mm transmission grating. Optical spectra were recorded using the Echelle Spectra Analyzer ESA 4000. In all cases the most intense emission lines were assigned to singly charged ions, however, lines corresponding to ions with higher charge were also recorded. In case of molecular gases the EUV spectra contained lines corresponding to singly or doubly charged ions. In optical range mainly molecular spectra were obtained. Based on spectral lines originating from ions electron temperature was estimated. Molecular spectra allowed for estimation of vibration and rotational temperatures.

10235-13, Session 3

Micro-X-ray fluorescence spectrometer with X-ray single bounce metallic capillary optics for light element analysis

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In the last 20 years, , due to the rapid development of X-ray optics, micro X-ray fluorescence spectrometry (micro-XRF) has become a powerful tool to determine the spatial distribution of major, minor, and trace ele-ments within a sample.

Micro-X-ray fluorescence (micro-XRF) spectrometers for light element analysis (6 ≤ Z ≤ 14) using glass polycapillary optics are usually designed and applied to confocal geometry. Two such X-ray optics systems are used in this setup. The first one focuses the primary beam on the sample; the second restricts the field of view of the detector. In order to be able to analyze a wider range of elements especialy with (6 ≤ Z ≤ 14), both sample and detector are under vacuum. Depth resolution varies between 100 ?m at 1 keV fluorescence energy (Na-K?) and 30 ?m for 17.5 keV (Mo-K?) [1,2].

In order to improve resolution at energies below 9 keV, our group designed similar spectrometer (in cooperation with PREVAC) but instead of primary polycapillary optics we applied single bounce metallic capillaries optics , designed and manufactured in our Laboratory. The vacuum chumber is currently under construction and is expected to be fully operational in September this year.

Single bounce gold capillaries with elliptic internal shape have recently been redesigned and developed in our Laboratory. Surface roughness was reduced up to 0.5 nm and slope error to 0.3 mrad. For these capillaries an expected depth resolution varies from 3 μm (1 keV) and 10 μm for 9 keV (Cu-K?).

The spectrometer equipped with gold capillaries offers the possibility of elemental analysis with better depth resolution than is offerred by glass polycapillaries at energies below 9 keV.

Furthermore, we will compare the capabilities and limitations of this spectrometer with others, that use laboratory and/or synchrotron sources.

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10235-15, Session 4

High-energy photoelectron spectroscopy combined to x-ray standing waves to study Pd/Y multilayers

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We use hard x-ray photoemission spectroscopy (HAXPES) combined with x-ray standing waves to characterize a series of Pd/Y multilayers designed to work in the 7.5-11 nm range. The samples, prepared by magnetron sputtering, are deposited either with or without nitrogen introduced in the sputtering gas or with or without a thin B4C barrier layer. The aimed period of the samples is 4 nm. The experiments consist in obtaining the core level spectra of the various elements for a series of grazing angles. The angular scan is made in the range given by the Bragg law, the multilayer period and the incident photon energy. Owing to the period of the multilayer and the presence of a 2.5 nm-thick capping layer, the photon energy is chosen to be 10 keV in order to probe the first 5-6 periods of the stack. Thus the Bragg angle is a little less than 1°. Rotating the sample enables putting the nodes of the electric field at some particular location of the stack, thus to make the excitation depth-selective, coming from one interface or another or from the center of one given layer. The changes of the chemical shift in the Pd 2p and 3d, Y 2p and 3d, N 1s, C 1s and B 1s as a function of the angle, that is to say as a function of the location in the stack will give information about the possible interfacial process taking place in the Pd/Y multilayers.

10235-16, Session 4

Multilayers on sculptured surfaces

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Multilayers grown on substrates with sculptured surfaces offer new functionalities and allow novel advanced x-ray optics and instrumentation. For example, multilayers deposited on saw-tooth substrates enable high efficiency Multilayer Blazed Gratings (MBG) which are a key component for high throughput and high resolution EUV and soft x-rays spectrometers. Understanding the fundamentals of x-ray diffraction in a sculptured multilayer stack and investigation of the growth of the multilayers on highly corrugated surfaces are of great importance for design optimization and performance of the MBGs. We found by simulations and confirmed by experiments that diffraction in MBGs corresponds to asymmetric Bragg diffraction of x-rays with specific refraction effects which depend on diffraction geometry and might significantly differ from the ones for the symmetrical diffraction in plane multilayers. The asymmetrical refraction alters the resonance wavelength, bandwidth, effective blaze angle, and diffraction efficiency of MBGs. Growth of multilayers at incline deposition which corresponds to growth geometry for highly faceted surface of saw-tooth substrates has been investigated. A new growth mode which results in highly periodical ripple patterns was discovered. Optimization of the deposition aimed to mitigate shadowing effects, roughening of interfaces of the multilayer stack, and excessive smoothing of the triangular groove shape has been performed. The optimal growth regime provided almost perfect replication of the saw-tooth substrate by the multilayer interfaces and allowed absolute diffraction efficiency close to the theoretical one. This work was supported by the US Department of Energy under contract number DE-AC02-05CH11231.

10235-17, Session 4

Development of depth-graded W/Si multilayer mirrors for X-ray focusing telescope application

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X-ray Timing and Polarization (XTP) telescope is proposed in China, by using the nested Wolter-I type optical system with large effective area, for the study of high energy physics at the region of 1-30 keV. High reflectance and low stress W/Si multilayers are demanded in the telescope to fulfill the spectral response and ensure the figure quality of the mirrors at the same time. A dedicated cylindrical deposition facility based on direct current magnetron sputtering technique was developed. Using this facility, W/Si multilayers fabricated under different base pressure and working pressure were tested to optimize the sputtering process. The microstructure and stress of W/Si multilayers with different d-spacing (d=2.7 nm-5.5 nm) and thickness ratio of W (?w=0.3-0.7) were studied. In order to obtain low stress multilayer mirrors, post-deposition annealing was applied on the multilayers and both the effects of temperature and annealing time were studied. Based on these works, a depth-graded W/Si multilayer was deposited on thin cylindrical mirror and the X-ray reflectivity was measured at Beijing Synchrotron Radiation Facility (BSRF).

10235-23, Session 4

Spectral X-ray glitches in monocrystalline diamond refractive lenses

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Recently we demonstrated [1, 2] that laser treatment nicely suits for the fabrication of diamond refractive lenses with large acceptance and high profile quality. Unique optical properties of monocrystalline diamond coupled with its excellent thermal stability allow such lenses to be applied as focusing, imaging and beam-conditioning elements at high-heat flux beams of today and future X-ray sources. However, as lenses are made from single crystal, the Bragg law can be satisfied, depending on crystallographic orientation of the lens substrate or on the photon energy of incident-to-lens X-rays. Due to the Bragg diffraction, transmitted intensity might be dramatically reduced. This problem is well known in X-ray spectroscopy and is called "glitch". In this paper, we demonstrate the existence of the diffraction in the focusing mode of the refractive lens and measure the magnitude of the effect.

A corresponding experiment was done at the BM31 at the ESRF and we observed presence of X-ray spectral glitches by monitoring an intensity transmitted through the CRL. Predictably, the effect arises at certain energies and affects lens' gain factor while keeping invariable a transmitted wave front. We noticed that contribution of X-ray glitches may be minimized by manufacturing of single lenses from various diamond plates with slightly different crystallographic orientation. In such case, the intensity drops are relatively small and may be comparable to X-ray glitches from monochromators, which have the drop value of 2-3%. To summarize, one can say that X-ray glitches from single-crystalline X-ray lenses may only impact spectroscopy or like experiments while the main part of the experiments with refractive optics (focusing, imaging, microscopy and diffraction) should ignore this effect.

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10235-18, Session 5

Lens-coupled tunable Young's double pinhole system for hard x-ray spatial coherence characterization

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During the last decades, a continuous development of x-ray sources, such as 3rd generation synchrotrons and free electron lasers, has resulted in a dramatic increase of coherence properties of a photon beam especially in the hard x-ray region. The wide availability of such highly coherent and brilliant x-ray beams has opened new opportunities for realization of new experimental techniques and also substantially increased a performance of existing methods such as phase contrast imaging, coherent diffraction imaging and interferometry [1-5]. The knowledge of the spatial coherence properties of the beams at x-ray sources is crucial for the scientific community and is very essential for the improvement of existing and development of new methods and instrumentation. One classical way to characterize the coherence is the Young's double slit technique where interference of two coherent beams created by two narrow slits occurs. This is a direct and straightforward technique to measure the spatial coherence and is widely used in the soft x-ray region [6,7]. A significant decrease of the synchrotron sources to a few microns makes its determination and the spatial coherence measurement more difficult: it is necessary to probe the different coherence length which requires in turn a set of pinholes with different split distances, and this obviously complicates the measurements. Moreover, downsizing the wavelength substantially increases the far field observation distance.

We proposed very compact experimental setup consisting of two apertures with variable separation distance and a compound refractive lens. The use of refractive lenses as a Fourier transformer makes possible to meet the far field registration conditions and greatly simplifies the scheme allowing the realization of a very compact experimental setup in comparison with the classical Young technique and its derivatives. Varying distance between the apertures provides a high sensitivity to the determination of the coherent properties of the source on low emittance synchrotrons in the hard x-ray region.

We would like to stress the fact that it is also possible to use this device to reveal the coherence propagation through a single optical component or the whole experimental setups at present high energy synchrotrons. In view of the future upgrade of the accelerator based sources our system will be particularly useful for the optimization of the parameters of electron beam optics including the emittance, since the length scale over which the coherence length will be measured is very large. We also foresee that the tunable pinholes interferometer could become a viable tool for single-pulse coherence characterization measurements at free-electron lasers.

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10235-19, Session 5

Metrology studies of soft X-ray and EUV grazing incidence optics using compact laser plasma light sources

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In this paper the use of laser plasma sources of soft X-rays and extreme ultraviolet (EUV) to test grazing incidence soft X-ray and EUV optics is presented. The sources are based on laser plasmas produced by irradiation of a gas puff target with nanosecond laser pulses at intensities in the interaction region of about 1011-1014 Wcm-2. The laser pulses are generated using commercially available Nd:YAG lasers generating 4 ns pulses with energy of about 0.8 J or pulses with time duration of 1 ns or 10 ns and energy of 10 J at 10 Hz repetition rate. The targets are formed by pulsed injection of working gas (Xe, Kr, Ar or their mixtures) in an additional annular stream of He gas under high-pressure using a double-nozzle set up (the double-stream gas puff target approach [1]). Spectral and spatial characteristics of radiation emitted from the source have been measured. The sources were used to test different grazing incidence optical systems for soft X-ray and EUV ranges, including an axisymmetric ellipsoidal mirror, a pair of axisymmetric paraboloid mirror, a Wolter-type hyperboloid/ellipsoid mirror and a multi-foil "lobster eye" mirror. Results of the metrology studies of these optical systems are presented. The possibility of the use of the laser plasma sources to test X-ray astronomy optics are briefly discussed.

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10235-20, Session 6

Polarizers tuned at key far-UV spectral lines for space instrumentation

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Polarimetry is a valuable technique to help us understand the role played by the coronal plasma in the energy transfer processes from the inner parts of the Sun to the outer space. Polarimetry in the far ultraviolet (FUV: 100-200 nm), which must be performed from space, supplies fundamental data of processes that are governed by the Doppler and Hanle effects on resonantly scattered line-emission. To observe these processes there are various key spectral lines in the FUV, from which H I Lyman alpha (121.6 nm) is the strongest one. Hence some solar physics missions that have been proposed or are under development plan to perform polarimetry at 121.6 nm, like the suborbital missions CLASP I (2015) and CLASP II (2018), and the proposed solar missions SolmeX and COMPASS and stellar mission Arago. Therefore, the development of efficient FUV linear polarizers may benefit these and other possible future missions.

High performance polarizers can be obtained with optimized coatings. Interference coatings can tune polarizers at the spectral line(s) of interest for solar and stellar physics. A polarizing coating for polarizers at 121.6 nm operating either by transmission or by reflection will be presented. Measurements on samples aged in nitrogen atmosphere resulted in good polarizer performance over time. Recently we have also developed coating beamsplitter polarizers that separate one polarization component by reflection and the other by transmission, which enables observing the two polarization components simultaneously with a single polarizer.

Coating polarizers for other spectral lines relevant for studies of solar and stellar magnetized atmospheres, such as C IV (154.8 nm) and Mg II (280 nm), are being developed.

The main results obtained on polarizers for key UV wavelengths will be presented.

10235-21, Session 6

Flat-field VLS spectrometers for laboratory applications

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We develop approaches to high-resolution stigmatic spectral imaging in the XUV (2 – 40 nm). A broadband stigmatic spectrometer makes combined use of a normal-incidence multilayer mirror (MM) (in particular, a broadband aperiodic MM) and a grazing-incidence varied line-space (VLS) reflection grating. The concave MM produces a slightly astigmatic image of the radiation source (for instance, the entrance slit), and the VLS grating produces a set of its dispersed stigmatic spectral images on the flat sensitive detector area. The spectral width of the operating range is defined by the multilayer structure of the MM and may range up to more than an octave in wavelength (e.g. 12.5–30 nm for an aperiodic Mo/Si MM). The stigmatism condition for the rays lying in the horizontal (dispersion) plane may be satisfied simultaneously for two wavelengths, e.g.14 and 27 nm. This is achieved at the expense of reducing by one the number of degrees of freedom of the optical configuration. In this case, the condition of non-rigorous stigmatism is fulfilled for the entire wavelength range selected. The existence of only a weak residual astigmatism signifies that the spectrograph forms two-dimensional spectral images of an object with a good spatial resolution along and across the dispersion direction throughout the operating range. Numerical ray tracing for a 1-m long spectrometer shows that the spectral images of a point source are all confined in a detector cell size (13 microns). To this end, plane VLS-gratings with a central line density of 600 1/mm were made by e-beam and interference lithography techniques. We have designed, aligned and tested a broadband stigmatic spectrometer for the 12.5 – 25 nm range. A LiF laser plasma spectrum was recorded in one 0.5-J laser shot. A spatial resolution of 25 microns and a spectral resolving power of 500 were demonstrated. This approach may be extended down to 6.9 nm using La/B4C MMs with barrier layers.

Another practical way to obtain ~10-micron spatial resolution in combination with high spectral resolution throughout a broad operating spectral range involves the use of a spherical VLS-grating jointly with a crossed grazing-incidence concave mirror. In this case, the grating-detector distance can be made constant to within a fraction of a millimeter, which favors attainment of high spatial resolution. We have designed a set of flat-field spectrometers of Harada type with concave VLS gratings for operation in the ranges 9–25, 5–20, and 20–110 nm. The overall sizes of the schemes are equal to 25, 50, and 150 cm.

A method was developed for calculating optical schemes for writing plane and concave VLS gratings with predefined line density variation by interference lithography techniques.

10235-22, Session 6

Effect of ion beam etching on the surface roughness of bare and silicon covered beryllium

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Due to the low density, high mechanical rigidity and thermal conductivity, ease of machining the Beryllium is one of the most promising materials for space mirrors, including studies for the solar corona in the wavelength range 13-30.4 nm. An obstacle to the widespread use of this material is its large surface roughness after mechanical polishing. In this paper, using samples of 200 nm thick beryllium films deposited on silicon substrates and polished bulk beryllium, we studied the main aspects of using ion-beam etching for finish polishing of beryllium. We present the results of investigation pertaining to the influence of the neon ion energy and angle of incidence on the beryllium films surface roughness. We measured the etching rates depending on the angle of incidence and energy of neon ions. We found that 400 eV is the optimal energy for neon ion etching ensuring slight surface roughness smoothing in the range of incidence angles of ± 40º. The deposition of 200 nm amorphous silicon films onto beryllium and their subsequent etching with the 800 eV argon ions improve the effective surface roughness integrated across the range of the spatial frequencies of 0.025-60 ?m-1, from Seff=1.37 nm down to Seff=0.29 nm. The effectiveness of the smoothing technology for x-ray applications, confirmed by the results of the study the reflective properties of the Mo/Si mirrors deposited on the substrate. The reflectivity at a wavelength of 13.5 nm increased from 2% for the substrates with the surface roughness of Seff=2.3 nm (the roughness value corresponds to the as-prepared bulk Be substrates and is taken from the literature) up to 67.5% after the smoothing technology.

10236-1, Session 1

Single-shot damage of Ru thin film induced by XUV FEL fs pulses *(Invited Paper)*

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The application of FEL sources requires the development of robust optical coatings that will survive after being exposed to high-repetition-rate, ultra-short, high-peak-intensity laser pulses. Understanding the mechanisms responsible for single- and multi-shot damage by fs pulses is crucial for predicting optics lifetime. Ruthenium (Ru) is chosen as a prospective material for XUV FEL grazing incidence optics due to its low oxidation rate combined with favorable optical constants.

This work focuses on studying the nature of single-shot damage of a 50nm thick Ru film on a Si substrate. Theoretical simulations using the two-temperature model (TTM) as well as experimental studies using scanning electron microscopy (SEM) and transmission electron microscopy (TEM) of irradiated spots were performed.

The TTM describes ultrafast heating of the Ru thin film induced by a 100fs pulse by considering electrons and phonons having different temperatures during the heating process. The laser energy is initially absorbed by the electrons at the metal surface. Heat diffusion by hot electrons into the depth takes place while simultaneously the energy is transferred to the still cold lattice by electron-phonon coupling.

As input for the TTM calculations knowledge of the thermal parameters is required. Frequency-domain thermo-reflectance measurements were used to extract the lattice heat capacity and the electron thermal conductivity for the studied Ru films. The electron heat capacity is taken to be proportional to the electron temperature using the experimentally obtained proportionality coefficient for bulk Ru. Also the electron-phonon coupling factor obtained for bulk Ru was used.

TEM study showed that exposures close to or slightly above the damage threshold fluence lead to the delamination of the upper part, about 10nm thick, of the Ru film. The TTM simulations showed that the high electron-phonon coupling factor in Ru causes a large lattice temperature gradient in the top of the Ru film which in turn is the reason of a high thermally-induced stress. This stress can explain the observed delamination of the top of the Ru layer.

10236-2, Session 1

Irradiation of EUV-mirrors with multiple FEL pulses below the single shot damage threshold

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A free-electron laser (FEL) is an intense source of quasi-monochromatic light. The FEL is proposed as source for lithography. As FEL output comes in intense ultra-short light pulses, optics and coatings are needed that can withstand these. It was shown that a single light pulse of 13.5 nm wavelength does not damage typical reflective coatings up to extremely high pulse energies per unit irradiated area. Critical single shot damage threshold (SSDT) levels have been reported to be 45 mJ/cm2 for normal-incidence reflective Mo/Si multilayer coatings (Ref. 1) and 80 mJ/cm2 at 4 degrees grazing incidence for amorphous carbon (Ref. 2). In lithography, optics are subject to large numbers of pulses. (Ref. 3). This paper describes the experimental determination of the multi shot damage threshold (MSDT) for grazing and normal incidence exposure of EUV coatings for 13.5 nm wavelength. The experiments have been executed at the Free-electron laser in Hamburg (FLASH). The exposures were performed for various fluences up to 10 % of the SSDT values for several materials and for various numbers of pulses up to 16M. After exposure, the change of reflectivity of 13.5 nm EUV light was measured at the exposed spots. The measurements showed that the reflectivity of coatings exposed to 10% of the SSDT for 16M pulses was slightly changed. These small changes are ascribed to non-optimum vacuum conditions of the experiment resulting in EUV induced surface modifications.

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10236-3, Session 1

Accumulative damage of ruthenium coated silicon exposed to multiple XUV pulses at 250 kHz-1 MHz repetition rate

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XUV and X-ray FELs provide quasi-monochromatic and extremely intense pulses of radiation. These allow the extension of studies of radiation-induced phase transitions of solids beyond the optical range, down to much shorter wavelengths. The length of pulses emitted by FELs is in the order of tens of femtoseconds, much shorter than typical time constants related to structural transformations and to energy transfer processes. Thus it is feasible to explore these processes separate from the rapid radiation absorption, which dramatically simplifies the modeling. The photon pulses can be applied separately or in series (trains) with a repetition rate up to a megahertz. FEL sources based on superconducting accelerating technology are especially suitable for a multi-shot mode of operation, in which the sample is exposed to a number of pulses at the same spot. For example, FLASH, a superconducting FEL in Hamburg, provides up to 800 XUV pulses of 10-100 fs each with a repetition rate up to 1 MHz. The multi-shot excitation of solid materials with XUV pulses offers a number of advantages. First of all, the energy deposition process is practically undisturbed by optical nonlinearities caused by processes such as multiphoton absorption and free carrier absorption. Moreover the absorption depth can be controlled by irradiation at an appropriate grazing incidence angle (e.g. below the critical angle). Thus, ultrashort XUV pulses provide a way to create well-defined excitation conditions in a very thin surface layer. In such a case the temperature gradients are very high and both the thermo-dynamical (heat transport, melting) and the thermo-mechanical processes (temperature induced strain) can be studied.

The role of accumulative processes on the multi-shot damage of thin layers of Ru optical coatings on a Si substrate was studied. Samples were exposed to intense monochromatic XUV radiation of 13.5 nm wavelength at grazing incidence below critical angle in a series of 1 - 400 femtosecond pulses with 250 kHz – 1 MHz repetition rate at the FLASH facility in Hamburg. Surface morphological and structural modifications formed as a result of accumulation were observed. They are threshold dependent on the mean fluence of the incident pulse train, with threshold values in the range of 0.1-0.5 J/cm2. Experimental results were supported by a two-temperature model describing heat transport and thermal melting. During the presentation, the physical mechanisms leading to the observed damage will be discussed and compared to the case of a bulk silicon sample exposed to 400 intense XUV pulses at normal incidence at 1 MHz [1].

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10236-4, Session 1

FEM approach to x-ray optics design

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In classical dynamical diffraction theory, the considered incident wave is usually either a plane wave, which refers to a source infinitely far from the diffracting crystal, or a so called spherical wave , which refers to a point-source located very close to the crystal surface[1]. However, many actual situations correspond to the intermediate case of a source at a finite distance from the sample Furthermore , the classical dynamical theory do not allow to deal directly with crystals of arbitrary shape ; in fact, the considered crystal surface is usually a planar surface [2].

Dynamical diffraction in a deformed crystal is described by the Takagi equations, which, in general, have to be solved numerically. All customary approaches [3-4], with some small differences, are based on a finite difference (FD) scheme, which can be easily implemented on a Cartesian mesh, but is not suitable for a deformed mesh. Practically, in all the numerical studies about diffraction in a deformed crystal, the crystal surface is always considered flat. The inner deformed crystal structure is then taken into account, but not the eventual deformation of the crystal surface.

Conversely, a finite-element method (FEM) can be easily applied to a deformed mesh and serves very well to the purpose of modelling an arbitrary incident wave on a deformed entrance surface.

FEM has many advantages: high flexibility in handling complex geometries, like for instance those designed to avoid back reflection of incident neutrons and, more generally, an automatic inclusion of boundary conditions in the integral formulation of FEM.

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10236-5, Session 2

Ultrafast laser-induced confined microexplosion: a new way to create new material phases *(Invited Paper)*

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Ultrafast laser induced microexplosion in confined geometry has already demonstrated the potential to create and preserve new thermodynamically non-equilibrium state of matter such as bcc-Al [1] and two tetragonal phases of Si [2]. These new phases have been predicted to exist theoretically, but have never before observed in nature or in laboratory experiments. New material phases formed under non-equilibrium conditions at pressures above 1012 Pa and temperatures exceeding 104 K, the conditions of the warm dense matter (WDM), have become accessible using micro-explosions triggered by ultra-short sub-ps pulse tightly focused in a micro-volume comparable to laser wavelength. These are conditions favourable for the breaking and re-arrangement of atoms into unusual material phases.

Here we present a new method for increasing the shock wave affected volume by using a micro-Bessel beam with a 100:1 aspect ratio [3]. The experimental results show an effective formation of voids when such a beam focused inside sapphire crystal, which is a clear indication of significantly increased efficiency of new phase formation when compared with the previous experiments with a Gaussian beam. The results open up a new way for increasing the quantity of high-density/pressure phases and help to increase sensitivity in search of new phases using X-ray and electron diffraction analysis.

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10236-6, Session 2

Ultrafast breakdown of dielectrics: new insight from double pump-probe experiments

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We investigate the mechanisms involved in the modification of dielectric materials by ultrashort laser pulses. We show that the use of a double pulse (fundamental and second harmonic of a Ti–Sa laser) excitation scheme allows getting new insight in the fundamental processes that occur during the interaction. We first measure the optical breakdown (OB) threshold map (intensity of first pulse versus intensity of second pulse) in various materials (Al2O3, MgO, ?-SiO2). Using a simple model that includes multiphoton excitation followed by carrier heating in the conduction band, and assuming that OB occurs when a critical amount of energy is deposited in the material, we can satisfactorily reproduce this evolution of optical breakdown thresholds. The results demonstrate the dominant role of carrier heating in the energy transfer from the laser pulse to the solid. This important phenomenon is also highlighted by the kinetic energy distribution of photoelectrons observed in a photoemission experiment performed under similar conditions of double pulse excitation. Furthermore, we show, in the case of ?-SiO2, that the formation of self-trapped exciton is in competition with the heating mechanism and thus play an important role especially when the pulse duration exceeds a few 100 fs. Finally, also in quartz or silica, we observe that the initial electronic excitation plays a key role in the formation of surface ripples and that their characteristics are determined by the first pulse, even at intensities well below OB threshold. The consequence of all these experimental results in the domain of UV or VUV induce damage will be discussed. In particular we demonstrate the possibility to dramatically increase the ablation efficiency by VUV light by using such double pulse scheme.

10236-7, Session 2

Development of a low-debris laser driven tape drive soft x-ray source

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This paper focuses on debris mitigation in a laser driven tape drive x-ray source. A smart design is being used to minimise the effect of shockwave reflection from the target's back and a continuous rough pumping is utilised to obtain an efficient purging of big lumpy debris particles out of the interaction chamber. The effect of low pressure (3-6 mbar) nitrogen buffer gas is studied together with a moderate magnetic field (0.14 Tesla) on both debris spall and hot ions trajectory was studied. The target material for this work is a 15µm VHS video tape composed of Mylar as carrier film with Fe2O3 and CrO2 powder. The experiments were conducted using a long pulsed 800ps, 50Hz Nd: YAG laser. The results obtained appeared to be promising in reducing the damaging effect of large debris particles (between 50 and 140 microns) as well as small particles (~5 microns) that deteriorates the efficiency of delicate optics.

10236-9, Session 2

Surface modification of BaF2 induced by focused 46.9-nm laser beam

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To study an interaction of a solid target with 46.9-nm laser radiation at a high irradiance, it is crucial to focus the laser into a small area. A multi-layer (ML) coated spherical mirror is usually used with a reflectivity of 15%-40% at a normal incidence. It is an effective way to focus 46.9-nm laser beam. However, the damage to ML coatings induced by the XUV laser radiation cannot be neglected in these focusing schemes. In our experiments, an uncoated SiC spherical mirror was also used to focus the 46.9-nm capillary-discharge laser. The reflectivity at 7.5 degree to the normal incidence was found to be 20%, which remained stable after 1000 laser shots fired. Monocrystalline BaF2 targets were irradiated by the focused XUV laser at various fluences. The surface modification was investigated by several techniques of microscopy and profiling. Although an XUV-LIPSS (Laser-Induced Periodic Surface Structures) formation is usually a rare phenomenon [1-3], two overlapping periodic structures were observed here. Wave vectors of these two grating-like structures are almost perpendicular. Spatial periods of these two structures are almost equal. In our previous work [4], periodic structures induced by the XUV laser on the surface of the same material at a ten times lower fluence (a grazing incident focusing scheme was engaged) were observed to be formed along one direction only, i.e., a single grating-like pattern was created under low-fluence irradiation conditions. It means that a

fluence of the XUV laser radiation plays an important role in the XUV-LIPSS formation. The BaF2 results will be compared to damage patterns obtained by our groups on the surface of other dielectrics, both inorganic and organic ones, exposed to short and ultra-short pulses of coherent XUV/x-ray radiation provided by various plasma- and e-beam-based lasers.

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10236-10, Session 3

Multiscale modelling of radiation chemistry: from picosecond processes to observable endpoints *(Invited Paper)*

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When exposed to intense radiation fields, chemical systems may reveal endpoint that depend not only on the dose applied, but also on the dose rate.

A multi-scale modelling approach has been developed to describe the long-term radiolysis of aqueous systems. This treatment uses a combination of stochastic track structure and track chemistry simulation as well as deterministic homogeneous chemistry techniques. It is comprised of four key programmatic elements:

• radiation track structure simulation,

• subsequent physicochemical processes,

• nonhomogeneous diffusion-reaction kinetic evolution, and

• homogeneous bulk chemistry modelling.

The first three components describe the physical and chemical evolution of an isolated radiation chemical track and provide radiolysis yields, within the extremely low dose isolated track paradigm. These yields are the input parameters for a bulk deterministic chemistry model.

This approach to radiation chemical modelling has been evaluated by comparison with the experimentally observed yields from the gamma and heavy ion radiolysis of water and of various aqueous solutions over a variety of applied dose and dose rates.

When reactions of secondary radiation-induced radicals produced by the chemistry of water radicals are important a complex radiation chemical system exists which is strongly dependent on secondary reaction processes. The ultimate observed chemistry is not just dependent upon the evolution of radiation track chemistry and the scavenging of the water radicals and their precursors, but also on the subsequent reactions of the products of these scavenging reactions with other water radiolysis products. Without the inclusion of intra-track chemistry in the chemical modelling, the deterministic component of the multi-scale model is unable to predict experimental data, highlighting the importance of intra-track radiation chemistry in the chemical evolution of the irradiated system.

10236-11, Session 3

Investigating laser-induced damage process in nanoparticles using femtosecond XFEL pulses *(Invited Paper)*

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Interest in high-resolution structure investigation has been zealous, especially with the advent of X-ray free electron lasers (XFELs). The intense and ultra-short X-ray laser pulses (~ 10 GW) pave new routes to explore structures and dynamics of single macromolecules, functional nanomaterials and complex electronic materials. In the last several years, we have developed XFEL single-shot diffraction imaging by probing ultrafast phase changes directly. Pump-probe single-shot imaging was realized by synchronizing femtosecond (<10 fs in FWHM) X-ray laser (probe) with femtosecond (50 fs) IR laser (pump) at better than 1 ps resolution. Nanoparticles under intense fs-laser pulses were investigated with fs XFEL pulses to provide insight into the irreversible particle damage processes with nanoscale resolution. Research effort, introduced, aims to extend the current spatio-temporal resolution beyond the present limit. We expect this single-shot dynamic imaging to open new science opportunity with XFELs.

10236-12, Session 3

Is there any dose-rate effect in breaking DNA strands by short pulses of extreme ultraviolet and soft x-ray radiation?

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Possible dose-rate effects in a plasmid DNA exposed to pulsed extreme ultraviolet (XUV) and soft x-ray (SXR) water window radiation from two different table-top plasma-based sources was studied. Dose delivered to the target molecule was controlled by attenuating the incident photon flux with aluminum thin foils as well as varying the DNA/buffer-salt ratio in the irradiated sample. Irradiated samples were analyzed using the agarose gel electrophoresis. Some additional bands were identified in gel electrophoretograms as results of a DNA cross-linking. They were inspected by atomic force microscopy (AFM). Yields of single- and double-strand breaks (Gy-1 Da-1) were determined as a function of incident dose rate. Both yields decreased with a dose rate increasing. The ratio of single- and double-strand breaks exhibited only a slight increase at elevated dose rates. In conclusion, complex and/or clustered damages do not seem to be initiated under these irradiation conditions.

10236-13, Session 4

Growth of nanodots on the grazing incidence mirror surface under FEL irradiation *(Invited Paper)*

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A new phenomenon on X-ray optics surfaces was observed: growth

of nano-dots (40–55 nm diameter, 8–13 nm height, 9.4 dots/?m2 surface density) on the grazing incidence mirror surface under the irradiation by the free electron laser (FEL) FLASH (5–45 nm wavelength, 3 degrees grazing incidence angle, 3 years mirror operation). With a model calculation we show that these nano-dots may occur during the growth of a contamination layer due to polymerization of incoming hydrocarbon molecules. The probability of polymerization is proportional to the density of photoelectrons in the point of the molecule dropping on a surface, which, in its turn, is proportional to the radiation power absorbed in the matter, i.e., the value of the field intensity on a surface. If the grazing angle is small compared to the critical angle of the total external reflection, the field intensity is low at the mirror surface, while it is increased in vacuum with increasing distance to the surface. Therefore, if there is a surface feature (a peak on a rough surface), the field intensity on its top is higher and, hence, the probability of polymerization of incoming molecules increases resulting in a quicker growth of the feature compared to the growth of underlying surface. As a result, the positive feedback arises: the higher the feature on the surface is, the quicker its growth occurs and finally the feature appears as nano-dot or spike in an AFM image. The crucial factors responsible for the growth of nano-dots in the model are the incident peak intensity and the reflection angle of the beam. The nano-dots growth proves to be observed in a limited window of grazing angle and intensity of incident radiation. In particular, a reduction of the peak intensity by several times only (e.g., replacement of FEL beam by synchrotron radiation) as well as a decrease of the grazing incident angle by just one degree (from 3 to 2 degrees) may result in the total disappearance of the nano-dots.

10236-14, Session 4

Low-pressure RF remote plasma cleaning of carbon-contaminated B4C-coated optics

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Boron carbide (B4C) - due to its exceptional mechanical properties - is one of the few existing materials that can withstand the extremely high brilliance of the photon beam from free electron lasers (FELs) and is thus of considerable interest for optical applications in this field. However, as in the case of many other optics operated at modern accelerator- or laser-based light source facilities, B4C-coated optics are subject to ubiquitous carbon contaminations. These contaminations, that are presumably produced via cracking of CHx and CO2 molecules by photoelectrons emitted from the surface of the optical components, represent a serious issue for the operation of the pertinent high performance beamlines due to a severe reduction of photon flux and beam coherence, not necessarily restricted to the photon energy range of the carbon K-edge. Thus, a variety of B4C cleaning technologies have been developed at different laboratories with varying success. Here, we present a study regarding the low-pressure RF plasma cleaning of a series of different types of carbon-contaminated B4C optical test samples via an inductively coupled O2/Ar and Ar/H2 remote RF plasma produced using the IBSS GV10x plasma source. Results regarding the chemistry, morphology as well as other aspects of the B4C optical coatings and surfaces before and after the plasma cleaning process will be reported.

10236-15, Session 4

Study of performance loss of Lyman alpha filters due to chemical contamination

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Observations in the UV and EUV allow many diagnostics of the outer layers of the stars and the Sun so that more and more space telescopes are developed to operate in this fundamental spectral range. However, absorption by residual contaminants coming from polymers outgassing causes critical effects. Indeed, the intensity of their absorption bands and the specific wavelengths depend greatly on the composition of the complex mixture of deposits. In case of in-orbit contamination, the optical properties of the surfaces may be degraded to varying extents: loss of signal, growth of noise, spectral shifts, stray light or linearity problems may appear and severely limit the quantitative interpretation of the in-flight data. Thus, a cleanliness and contamination control plan has to be defined as early as possible to mitigate the risk of damage of sensitive surfaces. It should cover all the project life cycle not only in orbit, but also on ground during AIT phases.

In order to quantify, and thus to specify the acceptable cleanliness level, it is paramount to improve our knowledge and understanding of contamination effects, especially in the UV/EUV range. Therefore, an experimental study has been carried out in collaboration between CNES and IAS, in the frame of the development of the Extreme UV Imager (EUI) suite. As part of the ESA Solar Orbiter mission, this instrument consists of two High Resolution Imagers and one Full Sun Imager designed for narrow pass-band EUV imaging of the solar corona at wavelengths between 17.4 nm and 121.6 nm, and thus very sensitive to contamination.

Here, we describe recent results of performance loss measured on representative optical samples of the most vulnerable surfaces exposed to the harmful space environment: six narrow pass-band filters, with a multilayer coating designed to select the solar Lyman Alpha emission ray around 121.6 nm, were contaminated with different amounts of typical chemical species. Since the optical characterization of VUV instrument components requires a very intense, continuous spectrum and a clean light source, the transmittance spectra were measured between 100 and 200 nm under high vacuum on the SOLEIL synchrotron beam line. They were compared before and after contamination, and also after a long exposure of the contaminated area to EUV-visible radiations, to evaluate the irreversible degradation due to photo-polymerization of the organic deposits. Moreover, FTIR spectra were measured to analyze the chemical evolution.

These results shall help us to better specify the cleanliness requirements for the space instrument during its development. In the longer term, these measurements will be useful to other future UV missions.

10236-17, Session 4

Non-thermal damage to lead tungstate induced by intense short-wavelength laser radiation

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Interaction of short-wavelength free-electron laser (FEL) beams with matter is undoubtedly a subject to extensive investigation in last decade. During the interaction various exotic states of matter, such as warm dense matter, may exist for a split second. Prior to irreversible damage or ablative removal of the target material, complicated electronic processes at the atomic level occur. As energetic photons impact the target, electrons from inner atomic shells are almost instantly photo-ionized, which may, in some special cases, cause bond weakening, even breaking of the covalent bonds, subsequently result to so-called non-thermal melting. The subject of our research is ablative damage to lead tungstate (PbWO4) induced by focused short-wavelength FEL pulses at different photon energies. Post-mortem analysis of complex damage patterns using the Raman spectroscopy, atomic-force (AFM) and Nomarski (DIC) microscopy confirms an existence of non-thermal melting induced by high-energy photons in the ionic monocrystalline target. Results obtained at Linac Coherent Light Source (LCLS), Free-electron in Hamburg (FLASH), and SPring-8 Compact SASE Source (SCSS) are presented in this Paper.

10236-18, Session 5

Thermalization of x-ray-generated electron cascades in diamond and LiF *(Invited Paper)*

Vladimir P. Lipp, Beata Ziaja-Motyka, DESY (Germany)

Irradiation with low-fluence X-ray pulses excites hot electrons within the material. In this talk we discuss the kinetics of the laser-excited electrons cascades as predicted with our classical Monte-Carlo simulations, based on the XCASCADE code. These simulations take into account the creation of laser-excited hot electrons and their elastic and inelastic collisions with ions. The model delivers the full temporal and spatial characteristics of the electron trajectories in various materials, including diamond and LiF. The comparison of the predicted electron range with the results of a recent XFEL experiment on LiF shows its reasonable agreement with the experimentally measured distribution of laser-generated color centers. In future, the code will be applied for simulations of hot carrier diffusion in X-ray-irradiated solids.

10236-19, Session 5

Analysis of various damage channels in FEL irradiated solids

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This contribution present modeling results of damage formation in solids irradiated with femtosecond free-electron X-ray laser pulses. The hybrid model XTANT (X-ray-induced Thermal And Nonthermal Transitions [1,2]) was used and extended where necessary to study different mechanisms of material damage. The model consists of a few modules interlinked with each other to tread a variety of processes occurring after an FEL irradiation: (a) Monte Carlo event-by-event simulation is applied for tracing photoabsorption and nonequilibrium electron kinetics of high-energy electrons and core holes; (b) Molecular Dynamics simulations is used for atomic kinetics, which evolves on time-dependent potential energy surfaces; (c) transferrable tight binding approach is used to obtain transient band structure of the material and the potential energy surface for atomic motion; (d) Boltzmann collision integrals are solved to obtain energy flow between electrons and ions (electron-phonon coupling). XTANT has recently been extended to include van der Waals potential contribution to long-range interatomic interaction, and Coulomb fields of ionized atoms when electrons are stripped and emitted from the surface.

Such a combination of approaches allows to study a variety of damage channels occurring in irradiated samples: (i) thermal melting of materials such as silicon [1], or GaAs; (ii) nonthermal melting in Si [1], or solid-solid phase transition in carbon [2]; (iii) Coulomb explosion of molecular crystal of C60, and ablation of amorphous carbon. Influence of various channels of electron-lattice energy exchange is analyzed. For example, calculated damage thresholds are in a very good agreement with experimental values for the variety of materials studied [1,5].

Comparison of calculated transient optical properties [3] with experimental ones measured in pump-probe experiments provides a possibility to benchmarks theoretical frameworks and approximations used in the numerical models. It is demonstrated that in case of semiconductors, shrinkage of the band gap due to atomic heating allows to extract information on electron-phonon coupling with femtosecond resolution in a broad range of electron temperatures [4].

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10236-8, Session PS

Formation of periodic relief at Sc/Si multilayer surface under EUV laser irradiation

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By methods of hard X-ray diffraction (?=0.154 nm) and scanning electron microscopy the surface morphology of Sc/Si multilayer mirrors influenced with nanosecond pulses of discharge capillary laser (?=46.9 nm) is studied. Under irradiation a relief of periodically alternating valleys and ridges is formed. The region of observed relief is extended over the space being ~104 greater than the irradiated region. Periodic relief (periodicity

of 2.2-2.3 ?m) appears as a result of reaction between Sc and Si layers making valleys (Sc3Si5 silicide) and ridges (ScSi monosilicide). Each of periods has complex structure exactly repeated in neighbor periods. Mechanisms of periodic relief formation are discussed.

10236-16, Session PS

Optical and structural characterization of Nb, Zr, Nb/Zr thin films on Si3N4 membranes windows

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High brilliance sources such as synchrotron and free electron laser (FEL) are very appealing for many applications in the development of science and technology. One strong requirement on the beam delivered by these sources besides brilliance, coherence and bandwidth is often related to the spectral purity; in fact the beam can be the superposition of various harmonics. The rejection of high harmonics or diffuse light in order to improve the quality of the beam can be achieved by suitable optical systems acting as band pass filters. (1-3)

Since materials present high absorption in the extreme ultraviolet (EUV) spectral range, the fabrication and the development of the devices as filters for the election of suitable spectral bandwidth or for the harmonics rejection is quite challenging. The FERMI FEL in Trieste is endowed with two FELs: FEL-1 covers the wavelength range 100-20nm and FEL-2 the wavelength range 20-4nm. (4). Nb and Zr are suitable materials for band pass filters development. In fact, simulation shows high transmittance and low absorption bands percentages in Zr and Nb filters in the same wavelength range that FEL-2 works (5). Furthermore they are very stables and reliable, suitable for e-beam deposition process (6), then perfect for the fabrication of filters to be inserted along synchrotrons beam lines and FEL transport optics.

IMD simulation shows good transmittance in the compound filter Nb/Zr, but diffusion between layers and interlayer formation could easily makes changes in the filters performances. Then the study of the interfaces properties is very critical and must be considered in order to improve the designing and the fabrication of new filters.

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Conference 10237: X-Ray Free-Electron Lasers: Advances in Source Development and Instrumentation

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10237-1, Session JS1

Investigating pathways of biological specimen on fs to μs timescales *(Invited Paper)*

Richard Neutze, Göteborgs Univ. (Sweden)

No Abstract Available

10237-2, Session JS1

Nonlinear X-ray spectroscopy: needs and prospects *(Invited Paper)*

Nina Rohringer, DESY (Germany)

In the soft x-ray range, coherent amplification of spontaneous x-ray emission [1] and stimulated resonant inelastic x-ray scattering (SRIXS) [2] have been demonstrated in Neon, with amplification levels of up to eight orders of magnitude. A next crucial step for advancing time resolved spectroscopy is the transfer of stimulated emission and SRIXS to the hard x-ray domain that would allow single-shot spectroscopy in chemically and biologically relevant samples in the liquid phase. Here, we present results of amplified spontaneous K-? emission in Manganese salts in aqueous solutions [3] with highly focused XFEL beams. Coherent amplification of the Mn K-? emission by four orders of magnitude and saturation of the signal has been demonstrated in MnCl2 one-molar solution. More excitingly, the chemical shifts of MnCl2 and KMnO4 aqueous solution is maintained in the strongly spectrally sharpened stimulated K-? emission spectra and coherent amplification has been shown at lower concentration. A more comprehensive technique for the study of chemical structure is SRIXS. Although demonstrated in Neon [2], the realisation of SRIXS in molecular targets is more difficult to achieve, even in the soft x-ray range [4-6] due to a smaller stimulated gain-cross section, that is distributed over many electronic, vibrational and rotational channels. We present two experimental studies, based on different two-colour XFEL schemes, that were specifically developed to achieve vibrationally resolved SRIXS in CO. In a first attempt [4], the XFEL was operated in a two-colour self-amplified spontaneous emission (SASE) scheme, with one frequency band tuned to the Oxygen ϖ^* resonance, and the other band overlapping with the Stokes-shifted emission frequencies. According to our theory [6], this setting should result in high-resolution SRIXS spectra by covariance analysis. Experimentally, the spectra are, however, contaminated by strong absorption features of molecular ions generated in competing processes. In a second experiment [6], the SASE pump pulse was replaced with a self-seeded, narrow-band pulse at considerably lower pulse energy that resulted in a significant decrease of the background. A comparison with theory shows that the experimental conditions were at the onset of an observable SRIXS signal, but so far, no statistical evidence is seen, to confidently report the demonstration of SXRIS in a molecular target. We however developed an experimental protocol that allows for the detection of relatively small SRIXS signals with highly fluctuating XFEL spectra. The challenges and the necessary experimental parameters to ultimately reach the conditions for stimulated x-ray emission spectroscopy in chemically relevant targets will be critically assessed.

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10237-3, Session JS2

Advanced time-domain diagnostics using photoelectrons *(Invited Paper)*

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Free-electron lasers (FELs) provide high-brightness, coherent X-ray pulse sources combining Angstrom spatial resolution with attosecond pulse durations. These unique properties open the door for a full 4D structural and simultaneous functional characterization of various kinds of complex systems, which has been a long-standing goal of molecular, material and biological science.

Deploying photoelectron streaking spectroscopy at an FEL we demonstrated a non-invasive, single-shot measurement of the X-ray pulse duration at the Linac Coherent Light Source (LCLS). This method is independent of photon energy, decoupled from machine parameters and provides an upper bound on the shortest FEL X-ray pulses available today, determining their duration to be on average no longer than 4.4 fs. Analysing the pulse sub-structure indicates a small percentage of the FEL pulses consisting of individual high-intensity spikes to be on the order of hundreds of attoseconds.

Recently, we developed a completely novel and extremely powerful approach for the characterization of the temporal and spectral FEL pulse structure—that is the application of the attoclock technique to the field of SASE free-electron lasers. This method of angular-resolved streaking is a combination of using a nearly circularly polarized infrared (IR) dressing field and a multi-channel time-of-flight (TOF) spectrometer. This instrument consists of a ring-like array of 16 TOF detectors arranged in a circle perpendicular to the propagation direction of the FEL and the co-linear streaking field.

For the first time, we were able to measure 16 simultaneous streaking spectra at the LCLS with various settings of the FEL. The goal is a complete FEL pulse structure characterization, including not only the duration and the central photon energy on a single-shot basis, but also the determination of the spectral phase of the train of attosecond sub-

spikes. At the same time, the relative strength of the streaking effect gives information about the arrival time shift of the pulses with respect to the laboratory frame from shot to shot.

The results include the direct characterization of the temporal structure of two-colour FEL pulses, allowing not only the determination of the duration of each of the two pulses independently, but also their temporal separation at the same time. These streaking measurements can be compared to simultaneous pulse duration measurements with the X-band rf transverse deflector XTCAV to give insight into the relative merits of these complementary techniques and into the fundamental mechanisms underlying the generation of FEL radiation in the process of self-amplified spontaneous emission (SASE). The findings assist the development of envisioned attosecond FEL pulse shaping and will pave the way to integrated online diagnostic tools for future high-repetition-rate or ultrashort-pulse X-ray laser facilities like European XFEL, LCLS-II and SwissFEL.

10237-4, Session JS2

Temporal diagnostics from photons: the experience with the PALM *(Invited Paper)*

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The Photon Arrival and Length Monitor (PALM), a THz streak camera device developed by PSI for non-destructive hard x-ray measurements of photon pulse length and arrival time versus a pump laser[1], was brought to the SACLA XFEL[2] in Japan in a cross-calibration temporal diagnostics campaign after an initial experiment where only the PALM was being used[3]. The device was used with 9 keV pink beam and a 9.0 and 8.8 keV two-color mode, successfully measuring the temporal ifnromation of the pulses for several different FEL operating conditions. The most interesting achievement is the PALM's ability to measure two arrival times of the two colorors as tey are shifted against each other by the FEL, opening up new possibilities in temporal accuracy for two-color experiments. SwissFEL will employ two such devices at the end stations for use by both operators and experimenters to improve the operation of the FEL and to better interpret experimental data.

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10237-5, Session 1

Overview of optics, photon diagnostics and experimental instruments at SACLA: development, operation and scientific applications *(Invited Paper)*

Kensuke Tono, Japan Synchrotron Radiation Research Institute (Japan)

Since the SPring-8 Angstrom Compact free electron LAser (SACLA) came into operation in 2011, it has been producing X-ray free-electron-laser (XFEL) light to offer research opportunities to users [1,2]. Now three beamlines (BLs 1-3) deliver stable XFEL beams by using robust X-ray optics (BL 1 for soft X-rays, BLs 2 and 3 for hard X-rays) [3]. Photon diagnostics at each BL makes a reliable evaluation of beam properties to contribute not only to the stable operation of the light source and BL, but also to the precise analysis of experimental data. The continuous development of end-station instruments such as detectors and sample injectors has been carried out to cope with the rapid evolution of experimental methods. These instruments were integrated to constitute user-friendly experimental platforms [4]. Along with the instrument development, we have established efficient procedures of the beamline operation to further accelerate the XFEL applications. These efforts have led to unique results in various scientific fields such as structural biology [5], nonlinear X-ray optics [6] and ultrafast physics and chemistry [7].

The development of new optics and experimental instruments is still going on. For example, multilayer mirrors for tight focusing will expand the frontier of X-ray science especially in X-ray quantum optics, high energy density science and nano-scale imaging. New experimental platforms are facilitating time-resolved measurement which generally requires complicated setups and procedures.

In this talk, I will give an overview on XFEL optics, photon diagnostics, experimental instrumentation and scientific applications at SACLA.

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10237-6, Session 1

Opportunities and challenges for photon diagnostics at the soft X-ray FEL FLASH in simultaneous operation mode *(Invited Paper)*

Marion Kuhlmann, Rolf Treusch, Elke Plönjes-Palm, Bart Faatz, Kai Tiedtke, Markus Braune, Barbara Keitel, Deutsches Elektronen-Synchrotron (Germany)

FLASH operates two distinguished undulator sections driven by one linear accelerator. In the 11th year of user operation the grown demands for detailed photon beam performances are doubled approached. The more complex machine settings and setup times require a more and more efficient determination of its characteristics concerning electron- and photon-beams.

The photon diagnostics systems, e.g. gas monitor detection, photon-ion spectroscopy, or diffractive tools, not only have to deal on a regular basis with fundamental wavelengths between 4nm and 90nm, also they have to be reliable from 1µJ up to 1mJ of average single pulse energy. For the success of the experiments the error bars of many diagnostics measurements need to be pushed into their current limits and developments to go further are always issued. Especial, the pulse duration in conjunction with the spectral width has been accessed in the last year. Direct approaches of fundamental wavelengths below the Nitrogene K-edge and higher harmonics in and below the water window were achieved.

While in principal distinguished to each other, the photon diagnostics tools of FLASH1 and FLASH2 add-up to a more complete understanding of the other. Together they allow for a better perspective towards further developments and a more suitable use of beam times. The intermingled knowledge of electron- and photon-beams is essential for an FEL particular in simultaneous operation mode. Examples out of regular user operation and distinguished FEL-studies are given to illustrate the current state of the photon diagnostics at FLASH.

10237-7, Session 1

Commissioning for the European XFEL facitiliy *(Invited Paper)*

Dirk Nölle, DESY (Germany)

The European XFEL is a 4th generation light source based on X-Ray Free-Electron-Lasers currently being commissioned in Hamburg, Germany. The core installation is a 17.5 GeV superconducting accelerator driving

3 SASE lines with photon energies up to the from 1 to beyond 20 keV range with a maximum of 27.000 pulses per second. The international facility is organized as a limited liability company with shareholder s from the contributing countries. DESY has taken over the leadership of the accelerator construction consortium, and will be in charge of the operation of the accelerator complex. The facility was set up with contributions from the shareholder counties, either being hardware systems and/or staff or cash contributions. The construction is almost complete, and the commissioning phase has started by the end of 2015.

This contribution will report the status of the accelerator complex with emphasis on the commissioning of accelerator and the commissioning of the SASE 1 FEL line with electron beam.

10237-8, Session 1

Starting up Swiss FEL *(Invited Paper)*

Luc Patthey, Paul Scherrer Institut (Switzerland)

No Abstract Available

10237-9, Session 1

Commissioning results of PAL-XFEL

Heung-Sik Kang, Hoon Heo, Chang-Ki Min, Changbum Kim, Haeryong Yang, Gyujin Kim, Pohang Accelerator Lab. (Korea, Republic of)

The Pohang Accelerator Laboratory's hard X-ray free electron laser, PAL-XFEL, achieved saturation of 0.144 nm FEL on 27 November 2016 using the 8-GeV electron beam and 100-m long undulators. The PAL-XFEL, located at Pohang, Republic of Korea, is a 0.1-nm hard X-ray FEL facility consisting of a 10-GeV S-band linac and 20 modules of 5-m long variable gap undulator. The construction project of the PAL-XFEL started in 2011 with the 5-year total budget of 400 MUSD, followed by its completion of building construction at the end of 2014 and the one-year installation of accelerator systems and beamlines. The accelerator commissioning started on 14 April 2016 with the first e-beam from a photo-cathode RF-gun, followed by the 10-GeV beam acceleration of 25 April 2016. Lasing of 0.5 nm FEL was achieved in June 2016 with the e-beam energy of 4 GeV, which is the third hard x-ray FEL ever achieved in the world following LCLS of 2009 and SACLA of 2011. In this paper we present the commissioning result of PAL-XFEL as well as the accelerator performances.

10237-10, Session 1

Attosecond Interferometry at FLASH *(Invited Paper)*

Tim Laarmann, DESY (Germany) and The Hamburg Centre for Ultrafast Imaging CUI (Germany)

Science with short-wavelength free-electron lasers (FELs) has enabled multiple breakthroughs covering the broad range from basic research in life sciences to applications in material science and catalysis. Particularly, the high degree of spatial coherence of the light field allows for key applications such as serial-femtosecond X-ray crystallography using the well-established and robust self-amplified spontaneous emission (SASE) of FELs [1]. Recently, temporal coherence provided by seeded FELs moved into the focus of interest [2-4]. It has been shown that full control over the light phase allows for a new class of light-phase sensitive experiments in the short-wavelength limit [5-7], such as non-linear four-wave mixing [8] and attosecond coherent control [9]. These give novel opportunities to study and possibly control energy and charge migration in molecular systems of increasing complexity with unprecedented spatial and temporal resolution. Here, we demonstrate phase control on the attosecond timescale in a Michelson-type all-reflective interferometric autocorrelator using monochromatic SASE pulses at a central wavelength of 38nm. The study paves the way towards utilization of advanced nonlinear methodologies even at partial coherent soft X-ray SASE FEL sources for watching the transformation of electronic orbitals in real time.

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10237-11, Session 1

Four-wave-mixing experiments and beyond: the TIMER/mini-TIMER setups at FERMI *(Invited Paper)*

Laura Foglia, Filippo Bencivenga, Riccardo Mincigrucci, Alberto Simoncig, Andrea Calvi, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Riccardo Cucini, Istituto Officina dei Materiali (Italy); Emiliano Principi, Emanuele Pedersoli, Flavio Capotondi, Maya Kiskinova, Claudio Masciovecchio, Elettra-Sincrotrone Trieste S.C.p.A. (Italy)

The development of free electron laser (FEL) sources, which provide XUV radiation of unprecedented coherence and almost transform-limited pulse structure [1], has opened up the realm of XUV non linear optics. Among the non-linear processes, third-order, or four-wave-mixing (FWM), interactions occur in all materials, independently of their symmetry, and are thus the most widely used in applications. In a FWM experiment, the control on the photon parameters (frequency, arrival time, polarization, etc.) of the three input photons allows to monitor, on ultrafast timescales, structural changes [2], spin [3] and electron [4] dynamics, collective phenomena [5] as well as to selectively probe correlations among different excitations [6].

The extension of FWM to the XUV regime, theoretically predicted [7] over a decade ago and demonstrated at mini-TIMER [8], adds elemental specificity and nano to atomic spatial resolution. This may allow, e.g., to probe correlations among low-energy excitations and core states, and to access the "mesoscopic" wavevector range (0.1-1 nm-1) [9], inaccessible so far and fundamental to investigate nanostructures and disordered systems. Here, we report on the latest evolution and future developments of TIMER and mini-TIMER setups, dedicated to FWM experiments. These include the use of multi-color FEL pulses for coherent Raman scattering [10] and the first observation of a FWM signal with "all-XUV" input beams. Nevertheless, TIMER and mini-TIMER are also suitable for time-resolved second order non-linear experiments, which are intrinsically surface sensitive due to symmetry restrictions, and we will discuss the foreseen extension of interface specific probing of electronic processes [11], e.g. charge and energy transfer, to the XUV, thus adding chemical specificity.

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10237-12, Session JS3

Development of free-electron laser at 30nm based on laser wake field accelerators *(Invited Paper)*

Ruxin Li, Wentao Wang, Jiansheng Liu, Yuxin Leng, Zhizhan Xu, Shanghai Institute of Optics and Fine Mechanics (China)

We will report the progress towards a free electron laser (FEL) at 30nm based on laser wake field accelerator. To achieve the high quality electron beam for driving the FEL, we have developed a two stage laser wake field accelerator. By designing a structured gas density profile between the dual-stage gas jets to manipulate electron seeding and energy chirp reversal for compressing the energy spread, we have experimentally produced high-brightness high-energy electron beams from a cascaded laser wakefield accelerator with peak energies in the range of 200-600 MeV, 0.4%-1.2% rms energy spread, 10-80 pC charge, and ?0.2 mrad rms divergence. The maximum six-dimensional brightness B6D, n is estimated as ?6.5 ? 1015 A/m2/0.1%, which is very close to the typical brightness of e beams from state-of-the-art linac drivers [1].

A new type undulator with transverse gradient [2] is implemented which can enhance the output by 20 times in comparison with the traditional undulator, according to the calculation. To obtain a fully coherent lasing output, a bright coherent soft-x-ray source at about 30nm based on the high order harmonic emission in argon [3] is used as a seeding source for the undulator. The FEL is at the final stage of experiments.

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10237-13, Session JS3

Towards sub-femtosecond X-ray FEL pulses *(Invited Paper)*

Agostino Marinelli, SLAC National Accelerator Lab. (United States)

No Abstract Available

10237-14, Session JS3

High-quality electron beams for high-quality FEL *(Invited Paper)*

Enrico M. Allaria, Elettra-Sincrotrone Trieste (Italy)

Thanks to the use of seeding, modern high gain FELs can now produce high power pulses with a longitudinal coherence much higher than normally available from SASE FELs. This possibility of fully coherent FEL pulses in the X-ray spectral range has several benefits for user's experiment and also it opens the door to new experimental possibilities such as coherent control experiments.

The achievement of a full coherence in the FEL pulses does not only requires a coherent seed but also needs an electron beam whose properties does not change over the length of the final FEL pulse. For this reason, requirements for electron beam quality in seeded FELs are significantly higher than for SASE FEL. Starting from the FERMI experience we report in the talk examples of small electron beam perturbation that have a large impact on FEL properties.

10237-34, Session PS

Magnetic force study for the helical afterburner for the European XFEL

Peng Li, Tao Wei, Yuhui Li, Joachim Pflüger, European XFEL GmbH (Germany)

At present the SASE3 undulator line at the European XFEL is using a planar undulator producing linear polarized soft X-ray radiation only. In order to satisfy the demand for circular polarized radiation a helical undulator system, the so-called afterburner is in construction. It will be operated as a radiator using the pre-bunched beam of the SASE3 undulator system. Among several options for the magnetic structure the Apple-X geometry was chosen. This is a pure permanent magnet undulator using NdFeB material. Four magnet arrays are arranged symmetrically the beam axis. Polarization can be changed by adjusting the phase shift (PS) between the two orthogonal structures. The field strength can be adjusted either by gap adjustment or alternatively by the amplitude shift (AS) scheme. For an engineering design the maximum values of forces and torques on each of the components under worst case operational conditions are important. The superposition principle is used to reduce calculation time. It is found that the maximum forces Fx, Fy and Fz for a 2m long Apple-X undulator are 1.8*10^4N, 2.4*10^4N and 2.3*10^4N, respectively. More results are presented in this paper.

10237-35, Session PS

Frequency doubler and two-color mode of operation at free electron laser FLASH2

Mikhail V. Yurkov, Marion Kuhlmann, Evgeny A. Schneidmiller, Deutsches Elektronen-Synchrotron (Germany)

We report on the results of the first operation of a frequency doubler at FLASH2. The scheme uses the feature of the variable gap of the undulator. Undulator is divided in two parts. The second part of the undulator is tuned to the double frequency of the first part. Amplification process in the first undulator part is stopped at the onset of the nonlinear regime, such that nonlinear higher harmonic bunching in the electron beam density becomes pronouncing, but the radiation level is still small to disturb the electron beam significantly. Modulated electron beam enters the second part of the undulator and generates radiation at the 2nd harmonic. Frequency doubler allows operation in a two-color mode and operation at shorter wavelengths with respect to standard SASE scheme. Tuning of the orbit , phase shifters and compression allows to tune intensities of the first and the second harmonic. The shortest wavelength of 3.1 nm (photon energy 400 eV) has been achieved with frequency doubler scheme, which is significantly below the design value for the standard SASE option.

10237-36, Session PS

Application of statistical techniques for characterization of SASE FEL radiation

Mikhail V. Yurkov, Evgeny A. Schneidmiller, Deutsches Elektronen-Synchrotron (Germany)

Radiation from the SASE FEL operating in the linear regime holds properties of completely chaotic polarized light. Measurements of the SASE FEL gain curve allows to determine saturation length which is strictly connected with coherence time. Statistical analysis of the

fluctuations of the radiation energies measured with different spatial apertures allows one to determine the number of the longitudinal and transverse modes. Thus, with these simple measurements it becomes possible to determine the degree of transverse coherence, coherence time, and photon pulse duration. In this report we present theoretical background and experimental results obtained at free electron laser FLASH.

10237-37, Session PS

A soft x-ray split-and-delay unit for FLASH II

Sebastian Roling, Matthias Rollnik, Westfälische Wilhelms-Univ. Münster (Germany); Marion Kuhlmann, Elke Plönjes-Palm, Deutsches Elektronen-Synchrotron (Germany); Frank Wahlert, Helmut Zacharias, Westfälische Wilhelms-Univ. Münster (Germany)

For the soft x-ray free-electron laser FLASH II at DESY in Hamburg a new split-and-delay unit (SDU) is built for photon energies in the range between 30 eV and 1500 eV with an option to expand this range to 2500 eV. The SDU is based on wavefront beam splitting at grazing incidence angles. A three dimensional set-up allows for the use of two different beam paths. With grazing angles of 1.3° in the fixed beam paths and 1.8° in the variable beam path a good compromise between a sufficient reflectance (shallow angles) and a large possible maximum delay (steeper angles) has been chosen. The maximum possible delay is ranges from -4 ps to +20 ps. For photon energies in the range between 30 eV and 800 eV the mirrors are coated with Ni providing a total transmission between T = 57 % at 30 eV and still T > 30 % at 800 eV. For photon energies up to 1800 eV a different beam path with platinum coated mirrors is used enabling a total transmission in the fixed beam path of T > 29 % at 800 eV and T = 24 % at 1800 eV, respectively. In the variable beam path the total transmission in this photon energy range is considerably lower with T = 13 % at 800 eV and T > 6 % at 1800 eV.

10237-38, Session PS

A hard x-ray split-and-delay unit for the HED Instrument at the European XFEL

Victor Kaercher, Westfälische Wilhelms-Univ. Münster (Germany); Liubov Samoylova, Karen Appel, European XFEL GmbH (Germany); Stefan Braun, Peter Gawlitza, Fraunhofer IWS Dresden (Germany); Frank Siewert, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Ulf Zastrau, European XFEL GmbH (Germany); Matthias Rollnik, Frank Wahlert, Helmut Zacharias, Westfälische Wilhelms-Univ. Münster (Germany)

For the High Energy Density Instrument (HED) at the European XFEL a hard x-ray split-and-delay unit (SDU) is built covering photon energies in the range between 5 keV and 24 keV. This SDU enables time-resolved x-ray pump / x-ray probe experiments as well as sequential diffractive imaging on a femtosecond to picosecond time scale. The set-up is based on wavefront splitting that has successfully been implemented at an autocorrelator at FLASH. The x-ray FEL pulses will be split by a sharp edge of a silicon mirror coated with Mo/B4C and W/B4C multilayers. Both partial beams then pass variable delay lines. For different wavelengths the angle of incidence onto the multilayer mirrors is adjusted in order to match the Bragg condition. Hence, maximum delays between +/- 1 ps at 24 keV and up to +/- 23 ps at 5 keV will be possible. Time-dependent wave-optics simulations are performed with SRW software. The XFEL radiation is simulated using the output of the time-dependent SASE code FAST. For the simulations diffraction on the beam splitter edge as well as height and slope errors of all eight mirror surfaces are taken into account. The impact of these effects on the ability to focus the beam by means of compound refractive lenses (CRL) are analyzed.

10237-39, Session PS

Duty-cycledependence of the filamentation effect in gas devices for high-repetition rate pulsed X-ray FELs

Yiping Feng, SLAC National Accelerator Lab. (United States)

Time-dependent simulations were carried out to study the duty-cycle dependence of the filamentation effect in gas attenuators and gas intensity monitors servicing a high repetition rate pulsed Free-electron laser beam. The evolution of the temperature/density gradients in-between the pulses in the entire gas volume, especially during the on-cycle, were obtained to evaluate the performance of any given pulse. It was found that the actual achieved attenuation in the attenuator or the intensity measured by the gas monitor deviates from the asymptotic value expected for a uniformly spaced pulse train after reaching a steady state, becoming progressively more significant as the duty-cycle tends lower

10237-40, Session PS

High-repetition rate experiments at the European XFEL

Thomas Tschentscher, European XFEL GmbH (Germany)

The European XFEL is located in the Hamburg Metropolitan areas in northern Germany. It is a large scale research infrastructure to provide users from academia and industry with highly intense, ultrashort and coherent x-ray pulses. X-ray photon energies span the regime from the carbon K-edge to beyond 20 keV. European XFEL will be the first hard x-ray FEL to provide an increased average brightness by means of generating up to approx.

30.000 electron bunches, respectively x-ray pulses per second. These pulses will serve several purposes of a user facility, but in particular they will allow to perform experiments sampling time scales from the sub-nanosecond level all the way to the millisecond level using up to thousands of x-ray pulses. This very unique feature will open the access to new experimental techniques and, therefore, new opportunities for scientific and technology applications.

In the presentation I will review the current concepts for providing, distributing and measuring the large number of pulses. The very high repetition rates beyond MHz certainly require specific technical solutions. Further several different areas of scientific application of these large repetition rates, wide ranging temporal resolutions and average fluxes will be presented.

10237-41, Session PS

Grating monochromator with ultrafast response for FLASH2 at DESY

Günter Brenner, Deutsches Elektronen-Synchrotron (Germany); Fabio Frassetto, CNR-IFN UoS Padova (Italy); Marion Kuhlmann, Elke Plönjes-Palm, Deutsches Elektronen-Synchrotron (Germany); Luca Poletto, CNR-IFN Padova (Italy)

We present the design of a monochromatic beamline explicitly designed for FLASH II at DESY. The monochromator is designed to be tunable in the 50-1000 eV energy range with a resolving power higher than 1000 and an instrumental response shorter than 100 fs in the whole energy range. Unfortunately, given the actual parameters of the FLASH2 emission (in particular the divergence and the wavelengths) and the restrictions in the positioning of the optical elements (the minimum distance from the source), the tilt of the pulse-front given by a single grating would give an unacceptable temporal stretching of the pulse at the output of the monochromator, that may be as high as 1 ps. This is not the case for X-rays FELs, where the source divergence and the wavelengths are

definitely smaller than in the extreme-ultraviolet and allow to use a single-grating design. The tilt has to be corrected by a second grating in the compensated configuration.

The optical design originates from the variable-line-spaced (VLS) grating monochromator, that uses a plane grating with VLS grooves illuminated in converging light. A second grating is added to compensate for the tilt of the pulse-front. The residual distortion of the pulse-front after the second grating, i.e. the instrumental response of the monochromator, is well below 10 fs.

The proposed design has several advantages: 1) it minimizes the number of optical elements, since just one grating is added with respect to a standard VLS monochromator beamline; 2) it requires simple mechanical movements, since only rotations are needed to perform the spectral scan; 3) it guarantees high performance in the whole energy range of operation; 4) it fits within the design requirements for the FLASH2 experimental hall.

10237-15, Session 2

Innovative FEL schemes using variable gap undulators *(Invited Paper)*

Evgeny A. Schneidmiller, Mikhail V. Yurkov, Deutsches Elektronen Synchrotron (Germany)

We discuss theoretical background and experimental verification of advanced schemes for X-ray FELs using variable gap undulators (harmonic lasing self-seeded FEL, reverse tape etc.) Harmonic lasing in XFELs is an opportunity to extend operating range of existing and planned X-ray FEL user facilities. Contrary to nonlinear harmonic generation, harmonic lasing can provide much more intense, stable, and narrow-band FEL beam which is easier to handle due to the suppressed fundamental. Another interesting application of harmonic lasing is Harmonic Lasing Self-Seeded (HLSS) FEL that allows to improve longitudinal coherence and spectral power of a SASE FEL. Recently this concept was successfully tested at FLASH2 in the wavelength range between 4.5 nm and 15 nm. That was also the first experimental demonstration of harmonic lasing in a high-gain FEL and at a short wavelength (before it worked only in infrared FEL oscillators). Another interesting scheme that was tested at FLASH2 is the reverse tapering that can be used to produce circularly polarized radiation from a dedicated afterburner with strongly suppressed linearly polarized radiation from the main undulator. An application of frequency doubling that allowed to reached the shortest wavelength at FLASH is discussed as well.

10237-16, Session 2

Statistical characterization of an X-ray FEL in the spectral domain

Alberto Lutman, Yiping Feng, Zhirong Huang, Jacek Krzywinski, Juhao Wu, Diling Zhu, SLAC (United States)

We experimentally characterize a Self Amplified Spontaneous Emission (SASE) Free Electron Laser (FEL) in the spectral domain. Spectra were measured in the Hard X-Rays (HXR) with a pair of single shot transmissive bent crystal spectrometers on single-shot basis. The relation between the resolution of both spectrometers was measured by analyzing the intensity distributions inside different bandwidths. The probability distribution of the intensity inside increasing monochormator bandwidths is studied in the different SASE regimes. The number of modes is confirmed to grow linearly in the exponential growth regime, but the growth is super-linear at saturation and in deeper saturation. We show also how the fluctuations decrease when a wider transverse portion of the beam is considered and give an estimate of the degree of transverse coherence.

10237-17, Session 2

Transverse coherence and pointing stability of the radiation from x-ray free electron lasers

Mikhail V. Yurkov, Evgeny A. Schneidmiller, Deutsches Elektronen-Synchrotron (Germany)

The radiation from SASE FEL has always limited value of the degree of transverse coherence. When transverse size of the electron beam significantly exceeds diffraction limit, the mode competition effect does not provide the selection of the ground mode, and spatial coherence degrades due to contribution of the higher order transverse modes. It is important that the most strong higher modes are azimythally non-symmetric which leads to fluctuations of the spot size and of the pointing stability of the photon beam [1-3]. These fluctuations are fundamental and originate from the shot noise in the electron beam. The effect of the pointing instability becomes more pronouncing for shorter wavelengths. We analyze in detail the case of optimized SASE FEL and derive universal dependencies applicable to all operating and planned x-ray FELs. It is shown that x-ray FELs driven by low energy electron beams will exhibit poor spatial coherence and bad pointing stability.

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10237-18, Session 2

Radiation properties of the SASE3 afterburner for European XFEL

Tao Wei, Peng Li, Yuhui Li, Joachim Pflüger, European XFEL GmbH (Germany)

The European XFEL SASE3 beamline is expected beam commissioning in 2017, at present all planar undulators are ready. In order to broaden the application of SASE3 beamline, several helical undulator segments was proposed to produce enhanced radiation from the micro-bunched electron beam, and this is commonly referred as an afterburner scheme. Because the degradation of energy spread and emittance will be exacerbated if the lower energy electron beam adopted, the prefer choice is producting afterburner FEL radiation at maximum beam energy. Thus the specific requirements of SASE3 afterburner have two points: ? 0.4-1.6nm linear polarized laser with ALL orientation @15GeV; ? 0.4-1.6nm helical polarized laser @15GeV. Delta undulator which developed recently at Cornell University and LCLS can provide full polarization control and compact structure, it seems a good choice for SASE3 afterburner. However, the influence of gradient magnetic field is so serious that the good field region unacceptable. In order to reduce the influence caused by gradient field, a novel apple-X undulator was proposed, which operated as variable-gap delta undulator and named by its movement way. In this article, Radiation properties of European XFEL SASE3 Afterburner in the presence of gradient field will be analysed. What's more, high-order magnetic field components exist in the apple-X undulator due to long period, this paper will derive the radiation output equations of high-order magnetic field undulator and validated with numerical simulation.

10237-19, Session 3

Hard X-ray wavefront diagnostics at X-FEL *(Invited Paper)*

Sebastien Berujon, Eric Ziegler, Elena-Ruxandra T. Cojocaru, Thierry Martin, ESRF - The European Synchrotron (France)

This presentation will review the stakes, challenges and solutions for X-ray pulse wavefront sensing. The work is based on developments achieved at synchrotron and XFEL where hard X-ray are available.

Emphasis will be put on the wavefront sensor developed in the frame of the EUCALL project.

Perspectives for wavefront sensing at emerging sources based on intense laser will also be discussed.

10237-20, Session 3

Laser power meters as x-ray intensity monitors for LCLS-II

Philip A. Heimann, Stefan P. Moeller, Sergio Carbajo Garcia, Sanghoon Song, Yiping Feng, James M. Glownia, David M. Fritz, SLAC National Accelerator Lab. (United States)

For the LCLS-II instruments we are developing laser power meters as compact intensity monitors that can operate at soft and tender X-ray photon energies. There is a need to monitor the relative X-ray intensity at various locations along an X-ray FEL beamline in order to observe a possible decrease in the reflectivity of X-ray mirrors. In addition for experiments, it is valuable to know the absolute intensity at the sample. There are two types of laser power meters based on thermopile and pyroelectric sensors. The thermopile power meters measure an average temperature and are compatible with the high repetition rates of LCLS-II. Pyroelectric power meters provide a pulse-by-pulse response. Ultra-high vacuum compatibility is being tested by residual gas analysis. An in-house development beamtime is being conducted at the LCLS SXR instrument. Measurements using both thermopile and pyroelectric power meters will be conducted at a set of photon energies in the soft X-ray range. The detectors' response will be compared with the gas monitor detector installed at the SXR instrument.

10237-21, Session 3

Single-shot beam intensity and position diagnostics for x-ray FEL's using gas fluorescence

Yiping Feng, Clemence Weninger, Matthieu Chollet, Diling Zhu, SLAC National Accelerator Lab. (United States)

We report the experimental demonstration of a new type of X-ray FEL intensity and position diagnostics using gas fluorescence. The measurement was carried out at the Linac Coherent Light Source using 7 keV hard X-rays propagating through ambient air. The nitrogen fluorescence emitted upon passage of the FEL beam were imaged using a highly sensitive optical setup, and there was sufficient optical yield that single-shot measurements were feasible. By taking two orthogonal and simultaneous images, the FEL beam trajectory could be determined in a nearly non-invasive manner, and is best suited for photon energies in the soft X-ray regime, where such a diagnostic capability has been largely unavailable up until now. The integrated intensity of the images could also serve as a non-invasive intensity monitor, complementary to current implementations of gas monitors. High repetition rate FEL's can also greatly benefit from such a new diagnostic tool for minimizing thermal damages.

10237-22, Session 3

Diagnosis of the nanosecond two-bunch mode for x-ray correlation spectroscopy experiments

Yanwen Sun, Diling Zhu, Sanghoon Song, SLAC National Accelerator Lab. (United States); Mark Sutton, McGill Univ. (Canada); Stephan O. Hruszkewycz, Argonne National Lab. (United States); Karl Ludwig, Boston Univ. (United States); Wojciech Roseker, Gerhard Grübel, Deutsches Elektronen-Synchrotron (Germany); Robert Aymeric, SLAC National Accelerator Lab. (United States); Brian Stephenson, Paul H. Fuoss, Argonne National Lab. (United States); Franz-Josef Decker, SLAC National Accelerator Lab. (United States)

Recently, at the Linac Coherent Light Source (LCLS), an accelerator based technique has been demonstrated to produce two x-ray pulses with ns-level time separations. This provided the opportunity to extend x-ray photon correlation spectroscopy (XPCS) techniques from milli- and microsecond timescales to the unexplored regime of nanosecond timescales. As the two pulses originates from two independent spontaneous amplified stimulated emission (SASE) lasing processes, beam properties fluctuates from pulse pair to pulse pair, as well as between the two pulses. On the other hand, two-pulse XPCS experiments require the pulse energy of the pulse pair to be either identical in the optimum cases, or with a known ratio. We first present non-destructive intensity diagnosis of the pulse pairs using a high-speed photodetector to measure the intensities of individual pulses within a pulse pair with time delays as short as 700 ps. The intensity diagnosis show better than 5%(rms) precision when the sum of the intensities from the two pulses are compared with the integrated measurement using a PIPS diode. Moreover, we show that the spatial overlap of the focused pulse pair at the sample plane can be monitored using small angle coherent scattering from of a static aerogel sample. With the help of the intensity diagnosis, we are able to classify the small angle scattering data based on intensity measurements of the two pulses. The speckle contrast from the pulse pairs with comparable intensities and those with intensities that are significantly different are compared. We observe degradation in speckle contrast in scattering patterns in the first case compared to the second, which is an indication that the two pulses were not fully overlapping at the sample plane.

10237-23, Session 4

Ultrahigh performance mirrors for diffraction limited light sources *(Invited Paper)*

Maurizio Vannoni, Idoia Freijo Martín, Harald Sinn, European XFEL GmbH (Germany)

All the major synchrotron radiation facilities around the world have recently started several upgrade projects to go towards the 4th generation of x-ray sources, in the direction of having fully "Diffraction Limited Storage Rings" (DLSRs). Several Free Electron Lasers (FELs), also providing diffraction limited beam, are operating and increasing their performances, while other ones are almost ready to be operational. To fully exploit the ultimate source properties of these next-generation light sources, the quality requirements for x-ray optics, especially mirrors, have significantly increased. To maintain the coherence of the beam, such optical components will feature shape accuracies in the nanometer regime over macroscopic length scales up to 1 meter. If we look on the ratio between these two parameters, we can quantify how challenging is not only the manufacturing process, but also the characterization and measurement operation.

In this talk we will explain better the challenges that are coming up, showing as examples the optical mirrors that will be used at European XFEL. The different steps of the processing of such mirrors will be detailed together with the method used for the surface characterization.

10237-24, Session 4

Soft x-ray optics for FEL applications *(Invited Paper)*

Sa?a Bajt, Deutsches Elektronen-Synchrotron (Germany)

The development of soft x-ray FELs, such as FLASH in Hamburg, Germany, and FERMI in Trieste, Italy, offer x-ray beams with special properties that can lead to exciting new science and applications. These FELs cover the energy region from several 10's to several 100's of eV in the first harmonic. In this region it is still possible to use normal incidence optics, based on multilayer coatings. Multilayer coatings are often used to increase the reflectivity of a mirror substrate but they also extend the angle at which such mirrors can be used. Although reflectivity peak of a multilayer coating is usually considered as a narrow bandwidth and this filtering effect is often desirable, it is wider that that of single crystals and better matches the FEL bandwidth. Multilayers usually have a repetitive, periodic structure, giving high reflectivity on the principle of constructive interference. On the other hand, since multilayers are manmade structures with full flexibility in materials and thicknesses, more complex design rules can be applied to emphasize certain characteristics, such as an increase in bandwidth. For example, one can design an aperiodic structure following an algorithm that seeks an optimum solution for the broadest bandwidth with the highest possible reflectivity. In this presentation I will present some examples of multilayer designs leading to narrow and broadband reflectivity, material combinations optimized for different wavelengths, and discuss how to suppress interface roughness and diffusion between layers. This is especially important in multilayers with extremely small periods (<2 nm) that are of interest for water window applications. I will also show different optics designs that enabled FEL beam focusing, dispersion, filtering and spectroscopy experiments. It is important to keep in mind that due to their high intensity FEL sources can also quickly modify or damage the optics. We are interested in understanding the causes of this damage and one of our goals is to find ways to extend their lifetime.

10237-25, Session 5

A hard x-ray split-and-delay optics with wavefront dividing crystals at SACLA *(Invited Paper)*

Taito Osaka, RIKEN SPring-8 Center (Japan) and Osaka University (Japan)

Coherent and ultrafast x-ray pulses from x-ray free-electron laser (XFEL) sources, such as SPring-8 Angstrom Compact free-electron LAser (SACLA) in Japan, have opened up new opportunities to investigate structural dynamics in atomic spatial and femtosecond time scales. A hard x-ray split-and-delay optical (SDO) system with perfect crystals, which produces monochromatic XFEL pulse pairs with a time delay ranging from femtosecond to nanosecond, will play an important role for performing novel approaches to reveal ultrafast dynamics involving x-ray–x-ray pump–probe and x-ray photon correlation spectroscopy methods. We have developed an SDO system with Si(220) crystals, which consists of two independent optical delay branches; path length variable and fixed branches. This two delay branch structure enables the production of a negative time delay as well as positive one up to 200 ps. The variable branch consists of two splitter/merger crystals and two reflector crystals, and the other fixed branch includes two channel-cut crystals. Since a beam axis propagating through the channel-cut crystals in the fixed branch is naturally parallel to the original axis, the use of them tremendously facilitates the alignment and operation of the SDO system. As the key optics, splitter/merger crystals, we tested edge-polished thick crystals at SACLA. Only a part of an XFEL pulse illuminating the crystal is reflected by the robust crystal, and the other part transmits straightly, which is so-called 'wavefront splitter'. The split pulses were focused ideally at the same spot by a Kirkpatrick–Baez type focusing mirror system. A time delay of zero between the split pulses is determined at few femtoseconds level via a two-beam interferometry, using wavefront divided pulses with nearly equal spectra.

10237-26, Session 5

Hard X-ray split-delay development at the Linac Coherent Light Source

Diling Zhu, Donald W. Schafer, SLAC National Accelerator Lab. (United States); Yanwen Sun, SLAC National Accelerator Lab. (United States) and Stanford Univ. (United States); Shi Hongliang, Justin H. James, Karl L. Gumerlock, Ted O. Osier, Randy Whitney, Josep Nicolas, Lin Zhang, Andrew H. Barada, Robert Aymeric, SLAC National Accelerator Lab. (United States)

The ability to split femtosecond free electron laser pulses and recombine them with an adjustable delay has promised numerous scientific applications such as double-pulse x-ray photon correlation spectroscopy and x-ray pump x-ray probe measurements. A wavefront-splitting-based hard x-ray split-delay system is currently under development at the Linac Coherent Light Source. The design configuration incorporates the horizontal scattering geometry in anticipation for the vertical polarization of the LCLS-II hard x-ray undulators. Si(220) crystal reflections were chosen, and a pair of large gap channel cut crystals were used for the fixed delay branch. The split-delay system covers the energy range between 7 and 12 keV and a delay range from -10 ps up to 500 ps. One of the primary technical challenges in the realization of such split-delay systems is how to maintain the spatial overlap of two micron-scale focal spots in the sample plane during the time delay adjustments. Our design features a planar air bearing based delay line to minimize the parasitic angular motion as well as to increase the overall stability of the crystal manipulation motion stacks. Insertable transmissive intensity diagnostics will also be present in between each crystals to enable alignment as well as drift monitoring. In this paper, we present the basic design concept, component by component tolerance analysis, the alignment procedure, and finally the performance estimation of the system. In addition, we show that a different split-delay concept based solely on channel cut crystals can be implemented to further increase long term stabilities, although at the cost of a decrease in its delay range.

10237-27, Session 5

Simulations of ultrafast x-ray laser experiments in EUCALL *(Invited Paper)*

Carsten Fortmann-Grote, European XFEL GmbH (Germany); Alexander A. Andreev, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany) and ELI-ALPS Research Institute (Hungary); Richard Briggs, ESRF - The European Synchrotron (France); Michael Bussmann, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Alexey V. Buzmakov, FSRC "Crystallography and Photonics", Russian Academy of Sciences (Russian Federation); Marco Garten, Alexander Grund, Axel Hübl, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Zoltan Jurek, Ctr. for Free-Electron Laser Science (Germany) and The Hamburg Ctr. for Ultrafast Imaging (Germany); Ne-Te D. Loh, National Univ. of Singapore (Singapore); Liubov Samoylova, European XFEL GmbH (Germany); Robin Santra, Ctr. for Free-Electron Laser Science (Germany) and The Hamburg Ctr. for Ultrafast Imaging (Germany) and Univ. Hamburg (Germany); Evgeny A. Schneidmiller, Deutsches Elektronen-Synchrotron (Germany); Ashutosh Sharma, ELI-ALPS Research Institute (Hungary); Thomas Tschentscher, European XFEL GmbH (Germany); Sergey Yakubov, Deutsches Elektronen-Synchrotron (Germany); Chun Hong Yoon, SLAC National Accelerator Lab. (United States); Michael V. Yurkov, Deutsches Elektronen-Synchrotron (Germany); Beata Ziaja, Ctr. for Free-Electron Laser Science (Germany) and The Hamburg Ctr. for Ultrafast Imaging (Germany) and Institute of Nuclear Physics, Polish Academy of Sciences (Poland); Adrian P. Mancuso, European XFEL GmbH (Germany)

Simulations of experiments at modern light sources, such as optical laser laboratories, synchrotrons, and free electron lasers, become increasingly important for the successful preparation, execution, and analysis of these experiments investigating ever more complex physical systems, e.g. biomolecules, complex materials, and ultra-short lived states of matter at extreme conditions.

We have implemented a platform for complete start-to-end simulations of various types of photon science experiments, tracking the radiation from the source through the beam transport optics to the sample or target under investigation, its interaction with and scattering from the sample, and registration in a photon detector.

This tool allows researchers and facility operators to simulate their experiments and instruments under real life conditions, identify promising and unattainable regions of the parameter space and ultimately make better use of valuable beamtime.

We present an overview of the status and future development of the simulation platform and discuss three applications: 1.) Single-particle imaging of biomolecules using x-ray free electron lasers and optimization of x-ray pulse properties, 2.) x-ray scattering diagnostics of hot dense plasmas in high power laser-matter interaction and identification of plasma instabilities, and 3.) x-ray absorption spectroscopy in warm dense matter created by high energy laser-matter interaction and pulse shape optimization for low-isentrope dynamic compression.

10237-28, Session 5

Design of compressors for free-electron-laser pulses using deformable gratings

Stefano Bonora, Nicola Fabris, Fabio Frassetto, Ennio Giovine, Paolo Miotti, CNR-Istituto di Fotonica e Nanotecnologie (Italy); Martino Quintavalla, Luca Poletto, CNR-IFN Padova (Italy)

We present the optical layout of soft X-rays compressors using reflective grating specifically designed to give both positive or negative group-delay dispersion (GDD). They are tailored for chirped-pulse-amplification experiments with FEL sources. The optical design originates from an existing compressor with plane gratings already realized and tested at FERMI, that has been demonstrated capable to introduce tunable negative GDD. Here, we discuss two novel designs for compressors using deformable gratings capable to give both negative and positive GDD. Two novel designs are discussed: 1) a design with two deformable gratings and an intermediate focus between the twos, that is demonstrated capable to introduce positive GDD; 2) a design with one deformable grating giving an intermediate focus, followed by a concave mirror and a plane grating, that is capable to give both positive and negative GDD depending on the distance between the second mirror and the second grating. Both the designs are tunable in wavelength and GDD, by acting on the deformable gratings, that are rotated to tune the wavelength and the GDD and deformed to introduce the radius required to keep the spectral focus. Both configurations are design for maximum throughput, since they have the minimum number of optical elements to give the desired GDD: two elements for configuration 1 and positive GDD, three elements for configuration 2 and positive/negative GDD. The effect of the actual FEL beam divergence on the compressor response is quantified. The deformable gratings have a laminar profile and are ruled on a thin silicon plane substrate. A piezoelectric actuator is glued on the back of the substrate and is actuated to give a radius of curvature that is varying from infinite (plane) to few meters. The ruling procedure, the piezoelectric actuator and the efficiency measurements in the soft X-rays will be presented. Finally, two test cases will be presented: a configuration tunable in the range 7-15 nm and a configuration tunable in the water window region (2-5 nm).

10237-29, Session 6

Fast refreshing target delivery systems for new generation light sources *(Invited Paper)*

Daniele Margarone, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

New generation light sources (high power lasers, free electron lasers and synchrotron sources) require advanced instruments for high repetition rate target delivery. This implies development of fast scanning systems, EMP-compatible motors and automation. Various solutions are currently being developed at new facilities under construction and some of them will be presented.

10237-30, Session 6

Detectors for intense, femtosecond X-ray sources *(Invited Paper)*

Bernd Schmitt, Paul Scherrer Institut (Switzerland)

No Abstract Available

10237-31, Session 6

Detector sustainability improvements at LCLS

Philip A. Hart, SLAC National Accelerator Lab. (United States)

Typical experimental conditions at LCLS pose a number of daunting and often unusual challenges to maintaining detectors, such as proximity to injectors, complex setups with moving components, intense FEL and optical laser light, and EMP. We, in collaboration with several other LCLS groups, have developed or are working on an array of engineering, monitoring, and administrative controls solutions to better address these issues. These include injector improvements and monitoring methods to prevent gas, liquid, arcing, or “ice” damage; fast online recognition algorithms to protect against signal-related damage; EMP mapping and amelioration; actively cooled filters; and more. Details of our running experience and recent improvements will be presented, along with discussion of future plans.

10237-32, Session 6

Bringing PW-class lasers to FELs *(Invited Paper)*

Hiromitsu Tomizawa, The Institute of Physical and Chemical Research (RIKEN Harima/SPring-8) (Japan)

Experimental researches using high power optical lasers combined with free electron lasers (FELs) open new frontiers in high energy density (HED) sciences. Probing and pumping capabilities are dramatically improved due to the brightness of the XFEL pulses with ultrafast duration. Besides, the peak intensities of Ti:sapphire laser Chirped Pulse Amplification (CPA) systems reach petawatt (PW)-class with operating in few tens of fs and commercially available at a few Hz of repetition rate. We have been developing an experimental platform for HED sciences using high power, high intensity optical lasers at the XFEL facility, SACLA. Currently, an experimental platform with a dual 0.5 PW Ti:Sapphire laser system is under beam commissioning for experiments combined with the SACLA's x-ray beam for research objectives that require more peak power in the optical laser pulses with a few tens of fs. The optical laser system is designed to deliver two laser beams simultaneously with the maximum power of 0.5 PW in each into a target chamber located in an experimental hutch 6 (EH6) at BL2, which was recently commissioned as a SACLA's 2nd hard x-ray beamline. A focusing capability using sets of compound refractive lenses will be applied to increase the x-ray fluence on the target sample. One of the most key issues for the integrated experimental platform is development of diagnostics that meets requirements both from the high power laser (e.g. resistance to harsh environments) and from the XFEL (e.g. adaptation to the available data acquisition system). The status and future perspective of the development including automatic laser alignment systems will be reported in the presentation. We will discuss the most promising and important new physics experiments that will be enabled by the combination of PW-class lasers and the world-class FEL's x-ray beam.

10237-33, Session 6

Integrating high-repetition rate high-energy/high-intensity laser to FEL experiments *(Invited Paper)*

Motoaki Nakatsutsumi, Gerd Priebe, Karen Appel, European XFEL GmbH (Germany); Carsten Baehtz, Helmholtz-Zentrum Dresden-Rossendorf e.V. (Germany); Thomas E. Cowan, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Sebastian Goede, Zuzana Konopkova, Max J. Lederer, European XFEL GmbH (Germany); Alexander Pelka, Toma Toncian, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Thomas Tschentscher, Ulf Zastrau, European XFEL GmbH (Germany); Bolun Chen, China Academy of Engineering Physics (China)

The combination of powerful optical lasers and an x-ray free-electron laser (XFEL) provides unique capabilities to study the transient behavior of matter in extreme conditions. The high energy density science instrument (HED instrument) at the European XFEL will provide the experimental platform on which an unique x-ray source can be combined with various types of high-power optical lasers. In this paper, we highlight selected scientific examples together with the associated x-ray techniques, with particular emphasis on femtosecond (fs)-timescale pump–probe experiments. Subsequently, we present the current design status of the HED instrument, outlining how the experiments could be performed. First user experiments will start at the beginning of 2018, after which various optical lasers will be commissioned and made available to the international scientific community.

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10238-1, Session 1

A 100 J-level nanosecond DPSSL for high-energy density experiments *(Invited Paper)*

Thomas J. Butcher, Paul D. Mason, Saumyabrata Banerjee, Klaus G. Ertel, P. Jonathan Phillips, Jodie M. Smith, Mariastefania De Vido, Oleg V. Chekhlov, STFC Rutherford Appleton Lab. (United Kingdom); Martin Divoky, Jan Pilar, HiLASE Ctr. (Czech Republic); Waseem Shaikh, Chris J. Hooker, STFC Rutherford Appleton Lab. (United Kingdom); Gerd Priebe, European XFEL GmbH (Germany); Toma Toncian, Helmholtz-Zentrum Dresden-Rossendorf e.V. (Germany); Cristina Hernandez-Gomez, STFC Rutherford Appleton Lab. (United Kingdom); Tomá? Mocek, HiLASE Ctr. (Czech Republic); Chris Edwards, John L. Collier, STFC Rutherford Appleton Lab. (United Kingdom)

Development of scalable, high energy diode pumped solid state lasers (DPSSLs) has become an increasingly important topic in recent years for a range of applications including materials processing; as pump sources for high-intensity PW class amplifiers; and for use in high energy density (HED) experiments in conjunction with high-brightness x-ray sources. The DiPOLE project at the Centre for Advanced Laser Technology and Applications (CALTA) within the Central Laser Facility (CLF) has, for some time, been developing an efficient high pulse energy DPSSL architecture based on cryogenic gas cooled, multi-slab ceramic Yb:YAG amplifier technology, capable of amplifying ns pulses to kJ pulse energies [1]. The technology has recently been proven capable of operating at 108 J at 1 Hz [2] as part of the DiPOLE100 system delivered to the HiLASE Centre [3] in the Czech Republic, the use for which will focus primarily on materials processing applications.

Following the success of this project CALTA has begun work on a second DiPOLE100 system for use at the European XFEL, specifically as part of the HED Beamline, where it will be used in shock compression experiments [4]. The nanosecond driving pulse that creates the initial shock for HED experiments has more stringent requirements than those used for materials processing or pumping. Small variations in the shot-to-shot energy or similarly small changes or ripples in the temporal pulse shape can lead to deleterious results, therefore stability and reproducibility of the drive laser is critical.

In this paper we will provide a brief update on the operational status of the DiPOLE100 system located at HiLASE and on the design changes that have been implemented in the next generation of DiPOLE100, which include a geometric redesign and enhancements to the pulse shaping capability of the system. Finally, we will comment on future projects and development underway at CALTA in this field.

[1] P. D. Mason et al, 'Scalable design for a high energy cryogenic gas cooled diode pumped laser amplifier', Applied. Optics, 54, 13, 4227-4238 (2015)

[2] S. Banerjee et al, '100??J-level nanosecond pulsed diode pumped solid state laser', Optics Letters, 41, 9, pp. 2089-2092 (2016)

[3] http://www.hilase.cz/en/ (2016)

[4] http://www.xfel.eu/research/instruments/hed

10238-2, Session 1

Performance results and design criteria of the power amplifiers in the L4 laser system

Axel Jochmann, Gilles Chériaux, Michael E. Donovan, Gavin Friedman, Erhard Gaul, Doug Hammond, James T. Heisler, Matt Kepler, National Energetics (United States); Daniel Kramer, Bedrich Rus, ELI Beamlines (Czech Republic); Todd Ditmire, National Energetics (United States)

The L4 laser system as part of ELI-Beamlines - the Czech pillar of the European project Extreme Light Infrastructure (ELI) – aims on producing multi-petawatt peak powers at unprecedented repetition rate.

The laser utilizes a broadband, ultra-high contrast front-end based on optical parametric amplification (OPCPA) in combination with large aperture mixed Nd:glass amplifiers. We report on the challenges, design criteria and latest performance results of these power amplifiers as a critical milestone towards the completion of this 10 PW laser system.

Managing the thermal load on these split-disk amplifier modules while maintaining superb beam quality allows repetition rates of one shot per minute for the full laser system.

At this rate the user will have a versatile tool to investigate the generation and application of new ultrafast laser driven light and particle sources in stand-alone or pump-probe scenarios.

10238-3, Session 1

Solution for testing large high-power laser lenses having long focal length

Denis Fappani, Monique IDE, Thales SESO (France)

Many high power laser facilities are in operation all around the world and include various tight optical components such as large focussing lenses. Such lenses exhibit generally long focal lengths which induces some issues for their optical testing during manufacturing and inspection. Indeed, their transmitted wave fronts need to be very accurate and interferometric testing is the baseline to achieve that. But, it is always a problem to manage simultaneously long testing distances and fine accuracies in such interferometry testing. Taking example of the large focusing lenses produced for the Orion experimentation at AWE (UK), the presentation will describe which kind of testing method has been developed to demonstrate simultaneously good performances with sufficiently good repeatability and absolute accuracy. Special emphasis will be made onto the optical manufacturing issues and interferometric testing solutions. Some ZEMAX results presenting the test set-up and the calibration method will be presented as well. The presentation will conclude with a brief overview of the existing "state of the art" at Thales SESO for these technologies.

10238-4, Session 1

All diode-pumped 4 Joule 527nm Nd:YLF laser for pumping Ti:Sapphire lasers

Faming Xu, Christopher J. Briggs, Jay Doster, Ryan Feeler, Edward F. Stephens, Northrop Grumman Cutting Edge Optronics (United States)

A new generation of diode-pumped solid-state lasers has been developed that enables ultra-stable Ti:Sapphire pumping at high energies. We report an injection-seeded, all diode-pumped high-energy Nd:YLF laser system based on a master oscillator power amplifier (MOPA) configuration. The laser produces pulses with over 4J of pulse energy at 10Hz, 527nm, and pulse duration of ~ 20ns. The laser is specifically designed to produce a uniform, flat-top beam in the near field.

Details of the laser design are discussed. The master oscillator is an injection seeded electro-optical Q-switched TEM00 mode laser. It produces stable, temporally-smooth laser pulses as the source for the system. The uniformity of the flat top beam is discussed. The pulse energy stability and beam pointing stability are thoroughly investigated and reported. The lifetime test results for the pump diodes are also presented.

In addition, test data from other lasers built using a similar design approach are presented to demonstrate the flexibility of the platform. First, data from a 10J, 1053nm, 20Hz, injection-seeded Nd:YLF laser is presented. Second, a 2J, 532nm, 10Hz, injection-seeded Nd:YAG laser is presented and the strengths and weaknesses of Nd:YAG and Nd:YLF are investigated. Last, data from several green lasers operating at > 150mJ and > 100Hz is presented.

10238-5, Session 1

A novel "gain chip" concept for high-power lasers

Min Li, Mingzhong Li, Zhenguo Wang, Xiongwei Yan, Xinying Jiang, Jiangang Zheng, Xudong Cui, Xiaomin Zhang, China Academy of Engineering Physics (China)

High-power lasers, including high-peak power lasers (HPPL) and high-average power lasers (HAPL), attract much interest for enormous variety of applications in inertial fusion energy (IFE), materials processing, defense, spectroscopy, and high-field physics research. To meet the requirements of high efficiency and quality, a "gain chip" concept is proposed to properly design the pumping, cooling and lasing fields. The gain chip mainly consists of the laser diode arrays, lens duct, rectangle wave guide and slab-shaped gain media. For the pumping field, the pump light will be compressed and homogenized by the lens duct to high irradiance with total internal reflection, and further coupled into the gain media through its two edge faces. For the cooling field, the coolant travels along the flow channel created by the adjacent slabs in the other two edge-face direction, and cool the lateral faces of the gain media. For the lasing field, the laser beam travels through the lateral faces and experiences minimum thermal wavefront distortions. Thereby, these three fields are in orthogonality offering more spatial freedom to handle them during the construction of the lasers. Transverse gradient doping profiles for HPPL and HAPL have been employed to achieve uniform gain distributions (UGD) within the gain media, respectively. This UGD will improve the management for both amplified spontaneous emission (ASE) and thermal behavior. Since each "gain chip" has its own pump source, power scaling can be easily achieved by placing identical "gain chips" along the laser beam axis without disturbing the gain and thermal distributions. To detail our concept, a 1-kJ pulsed amplifier is designed and optical-to-optical efficiency up to 40% has been obtained. We believe that with proper coolant (gas or liquid) and gain media (Yb:YAG, Nd:glass or Nd:YAG) our "gain chip" concept might provide a general configuration for high-power lasers with high efficiency and quality.

10238-6, Session 1

10J water-cooled DPSSL system based on Yb:YAG crystal edge-cladded by Cr:YAG ceramics

Jian-Gang Zheng, China Academy of Engineering Physics (China) and Shanghai Jiao Tong Univ. (China); Xiongwei Yan, Xinying Jiang, Zhenguo Wang, Mingzhong Li, Jun Zhang, China Academy of Engineering Physics (China); Qihua Zhu, Wanguo Zheng, China Academy of Engineering Physics (China) and Shanghai Jiao Tong Univ. (China)

Laser Inertial Fusion Energy (IFE) has been attracting the interests of the researchers around the world, because of the promising to the future energy. The Yb:YAG was broadly used in the research field of high-peak power and large energy laser with repetition-rate for IFE because of its outstanding performance, including significant thermal and mechanical capacities, long upper energy level lifetime, high quantum efficiency and highly doping capacity. But it exhibits high saturation fluence at room temperature because of the small emission and absorption cross-section. And at the same time this gain material exhibits self-absorption of laser because of the thermal population at lower laser level at room temperature. Ant it appears to have been solved by means of the cryogenic temperature, but the total efficiency of the laser system will be decreased as the use of cryogenic temperature.

The amplified spontaneous emission (ASE) effect of the amplifier can be relaxed by means of edge-cladded absorption material. And the difficulties of edge cladding can be will solved as the emergence of ceramics. But at present the ceramics exhibits high scattering and many disfigurements, which limited the application in the high-power large-energy laser system. So the edge-cladding of Yb:YAG crystal will be a key issue for solution the ASE in amplifier.

In this paper, we will introduce a 10J water-cooled DPSSL system, based on Yb:YAG crystal at room temperature. In this system a new edge cladding method has been used, that the Yb:YAG crystal was edge cladded by Cr:YAG ceramics, which was used as the absorption material of ASE. The amplifier was an active mirror water-cooled room temperature amplifier. With the help of this edge cladding the ASE has been lowered, and about 5 times small signal gain has been obtained in a single pass amplification, which was much higher than the earlier of 2 times. And the wavefront aberrance of the laser beam was also reduced due to the thermal equilibrium between the edge cladding and the gain region. the amplifiers can be stably operated under 10Hz. Finally the output of the laser system was about 7.15J@10Hz and 10.8J@1-2Hz. The total optical-to-optical efficiency was about 8.3% for 1-2Hz (under the condition of 120kW/1ms pumping, 880mJ input and 10.8J output) and 5.6% for 10Hz.

10238-7, Session 2

5 Hz high-energy, ultrahigh contrast OPCPA frontend for the L4 laser system *(Invited Paper)*

Gilles Chériaux, National Energetics (United States); Roman Antipenkov, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Teddy Borger, The Univ. of Texas at Austin (United States); Gavin Friedman, National Energetics (United States); Jonathan T. Green, ELI Beamlines (Czech Republic); Doug Hammond, James T. Heisler, Axel Jochmann, Nirmala Kandalai, Matt Kepler, National Energetics (United States); Daniel Kramer, Bedrich Rus, ELI Beamlines (Czech Republic); Erhard Gaul, Todd Ditmire, National Energetics (United States)

The need of novel light- and particle sources for basic and applied research stimulates the development of high intensity lasers as their drivers. As part of the ELI (Extreme Light Infrastructure) project, ELI-Beamlines will serve the user with multiple laser systems to span intensities from multi terawatt at kilohertz repetition rate to multi petawatt pulses at one shot per minute.

These systems will allow programmatic research in generation and applications of high-intensity X-ray sources, particle acceleration, and HED physics related studies.

In general these systems can be divided in two classes: a class of broadband short-pulse laser systems (<50 fs) primarily based on Ti:Sapphire and another class of high-energy laser systems with longer pulse duration (100 fs...1 ps) based on neodymium or ytterbium glass or crystals as the active media.

Based on Nd:glass, the L4 beam line, a 10 PW (1.5 kJ and 150 fs) at 1 shot every minute will be delivered by National Energetics to ELI-Beamlines.

At laser intensities greater than 1021 W/cm2, a temporal contrast of >1011 is required for most of the intended experiments. For this reason, a

double CPA frontend system based on optical parametric amplification in combination with a novel nonlinear pulse cleaning scheme was designed. To seed the subsequent high energy power amplifiers, it is required to control spatial and spectral pulse shape to efficiently extract energy from the following kJ class laser heads.

We present data from the fully characterized frontend which meets the milestone requirements to seed the main amplifiers of the L4 laser system. Joule class pulse energies at 5 Hz repetition rate through five amplification stages define a new record for unprecedented high average power for OPA laser systems.

10238-8, Session 2

Active spectral pre-shaping with polarization encoded amplifiers

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Polarization encoded (PE) Ti:sapphire amplifier can easily pre-shape the spectrum of amplified pulses. This property can be used to compensate for the spectral red-shifting and gain narrowing that are typically observed in Ti:Sapphire lasers. We demonstrate experimentally that active pre-shaping of the pulse spectrum in a PE amplifier combined with saturated amplification in the following conventional amplifier can conserve and even broaden the overall amplification bandwidth.

A combined amplifier that includes PE- amplification (during the first passes) and a conventional one in the following saturation phase is also proposed and studied by computer modelling. This allows to achieve both the broad bandwidth and high efficiency in a single amplifier. A 5 passes combined PE amplifier was simulated. The seed was firstly amplified by 3 passes with the PE amplification scheme, then the seed was decoded and directed back to the crystal for 2 additional passes of a saturated conventional amplification. Because the seed was already decoded before the last saturation passes in the amplifier, the energy extraction efficiency reached 44% which is similar to that of a conventional Ti:sapphire amplifier. The amplified bandwidth of 125 nm was obtained with a Gaussian seed spectrum of 100nm.

We show experimentally that the decoding efficiency of PE amplifier can be optimized by changing the thickness of the decoding quartz. At gain of ~30, the decoding efficiency of ~75% was achieved with the thickness of the decoding quartz of 35.1mm (thickness of the encoding quartz was 17.4mm), while the decoding efficiency of 80% was reached at gain of ~10. It shows that smaller gain guaranties better efficiency and also a smoother spectral profile.

The compressibility of the PE amplified pulses close to the transform limit is verified experimentally.

10238-9, Session 2

Dispersion measurement on chirped mirrors at arbitrary incidence angle and polarization state

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The optical elements of femtosecond high peak power lasers have to fulfill more and more strict requirements in order to support pulses with high intensity and broad spectrum. In most cases chirped pulse amplification scheme is used to generate high peak power ultrashort laser pulses, where a very precise control of spectral intensity and spectral phase is required in reaching transform-limited temporal shape at the output. In the case of few cycle regime, the conventional bulk glass, prism-, grating- and their combination based compressors are not sufficient anymore, due to undesirable nonlinear effects in their material and proneness to optical damages. The chirped mirrors are also commonly used to complete the compression after a beam transport system just before the target. Moreover, the manufacturing technology requires quality checks right after production and over the lifetime of the mirror as well, since undesired deposition on the surface can lead alteration from the designed value over a large part of the aperture. For the high harmonic generation, polarization gating technology is used to generate single attosecond pulses [1]. In this case the pulse to be compressed has various polarization state falling to the chirped mirrors. For this reason, it is crucial to measure the dispersion of the mirrors for the different polarization states.

In this presentation we demonstrate a simple technique to measure the dispersion of arbitrary mirror at angles of incidence from 0 to 55 degree, even for a 12" optics. A large aperture 4" mirror has been scanned over with micrometer accuracy and the dispersion property through the surface has been investigated with a stable interference fringes in that robust geometry. We used Spectrally Resolved Interferometry, which is based on a Michaelson interferometer and a combined visible and infrared spectrometer. Tungsten halogen lamp with 10 mW coupled optical power was used as a white-light source so with the selected spectrometer we could investigate over the 500-1300 nm spectral range. We also measured the mirrors with broadband oscillator pulses, and we found that the dispersion was the same for both light source. Group Delay Dispersion was obtained with a ±2 fs^2 accuracy from the Fourier Transform method of the interference fringes. Using an adjunct mirror, we made possible to change continuously the angle of incidence at the chirped mirror within 3 and 55°. On the input part of the interferometer we placed a wire-grid polarizer, and sensitivity of the chirp mirrors to the polarization state have been measured at different incidence angles. To present the flexibility of the device we scanned two different compressor mirrors with +100 fs^2 and -500 fs^2 at the 800 nm central wavelength. We separately developed an optical arrangement to detect Group Delay shift between s and p polarization reflections of large aperture chirped compressor mirrors and we found that it's below the detection limit, so further investigation will be necessary.

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10238-10, Session 3

Picosecond temporal contrast of Ti:Sapphire lasers *(Invited Paper)*

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The temporal shape of recompressed Ti:sapphire CPA pulses typically contains relatively long pre- and post- pedestals appearing on a picosecond time scale. Despite playing a key role in laser-matter interactions, these artifacts – especially the shape of the leading front of the recompressed pulses – are poorly investigated and understood. The related publications consider picosecond pedestals appearing at both fronts of the main pulse to be related to scattering of the stretched pulse off diffraction gratings inside the stretcher or due to clipping of the pulse spectrum at dielectric coatings. In our experiments we analyzed different types of stretcher-compressor combinations used in Ti:Sapphire laser systems. These include a prism-based stretcher and a bulk compressor, transmission and reflection diffraction gratings - based combinations. We identified pedestals that are typical for the particular stretcher-compressor combination. Especially investigated are those which are coherent with the major recompressed pulse, since with self-phase modulation in power amplifiers they will grow nonlinearly and finally appear symmetric around the major pulse, generating the pre-pedestal from the post-pedestal. Thus, a previously unreported influence of the trailing pedestal has been identified. It is commonly known that recompressed pulses from Ti:sapphire chirped-pulse amplifier systems are accompanied by a slowly decaying ragged post-pedestal. The detailed investigation shows that it consists of numerous pulses with temporal separation in the picosecond range. These are coherent with the main pulse. Moreover, the temporal structure of the trailing pedestal is independent of the particular realization of the Ti:sapphire system and it is present in radiation of any Ti:Sapphire CPA system including Kerr-mode locked master oscillators. Our investigations show that the coherent ragged post-pedestal is the post-radiation of inverted Ti:sapphire medium resulting from phonon-photon interactions.

10238-11, Session 3

Thin Disk Ti:Sapphire amplifiers for Joule-class ultrashort pulses with high repetition rate

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High peak power CPA laser systems can deliver now few petawatt pulses [1]. Reaching the high energies with broad spectral bandwidth necessary for these pulses was possible by the use of large aperture Ti:Sa crystals as final amplifier media. Wide applications for these systems will be possible if the repetition rate could be increased. Therefore, thermal deposition in Ti:Sa amplifiers is a key issue, which has to be solved in case of high average power pumping. The thin disk (TD) laser technology, which is intensively developed nowadays by using new laser materials, is able to overcome thermal distortions and damages of laser crystals [2]. TD technique also has the potential to be used in systems with both high peak and average power. For this, the commonly used laser materials with low absorption and emission cross sections, also low heat conductivity, like Yb:YAG, need to be replaced by a gain medium that supports broad enough emission spectrum and high thermal conductivity to obtain few tens of fs pulses with high repetition rates. Parasitic effects during the amplification process however seriously limit the energy that can be extracted from the gain medium and also they distort the gain profile. Nevertheless, the application of the Extraction During Pumping (EDP) technique can mitigate the depopulation losses in the gain medium with high aspect ratio [3]. We proposed to use Ti:Sa in combination with TD and EDP techniques to reach high energies at high repetition rates, and we presented numerical simulations for different amplifier geometries and parameters of the amplification [4,5].

We present the results of the proof-of-principle experiment, where a EDP-TD Ti:Sa amplifier was tested for the first time. In our experiment, the final cryogenically cooled Ti:Sa amplifier in a 100 TW/10 Hz/28 fs laser system was replaced with the EDP-TD room temperature cooled arrangement. Amplified seed pulse energy of 2.6 J was reached only for 3 passes through TD with 0.5 J of input seed and 5 J of absorbed pump energy. We verified the excellent heat extraction capabilities of our amplifier module. Results of the scaling simulations on the base of this experiment for 100s of TW peak power laser systems operating at up to 100 Hz will be also presented.

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10238-12, Session 3

Measurement of spectral phase noise in a cryogenically cooled Ti:Sa amplifier

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In most of cases the drift of the carrier envelope phase (CEP) of a chirped pulse amplifier (CPA) system is determined only [1], being the relevant parameter at laser-matter interactions. The need of coherent combination of multiple amplifier channels to further increase the peak power of pulses requires interferometric precision [2]. For this purpose, the stability of the group delay of the pulses may become equally important. Further development of amplifier systems requires the investigation of phase noise contributions of individual subsystems, like amplifier stages. Spectrally resolved interferometry (SRI), which is a completely linear optical method, makes the measurement of spectral phase noise possible of basically any part of a laser system [3]. By utilizing this method, the CEP stability of water-cooled Ti:Sa based amplifiers was investigated just recently, where the effects of seed and pump energy, repetition rate, and the cooling crystal mounts were thoroughly measured [4].

We present a systematic investigation on the noise of the spectral phase, including CEP, of laser pulses amplified in a cryogenically-cooled Ti:Sa amplifier of a CPA chain. The double-pass amplifier was built in the sample arm of a compact Michelson interferometer. The Ti:Sa crystal was cooled below 30 °K. The inherent phase noise was measured for different operation modes, as at various repetition rates, and pump depletion. Noise contributions of the vacuum pumps and the cryogenic refrigerator were found to be 43 and 47 mrad, respectively. We have also identified CEP noise having thermal as well as mechanical origin. Both showed a monotonically decreasing tendency towards higher repetition rates. We found that the widths of the noise distributions are getting broader towards lower repetition rates. Spectral phase noise with and without amplification was measured, and we found no significant difference in the phase noise distributions. The mechanical vibration was also measured in the setup by using an accelerometer synchronously with the optical measurements. The noise spectra of phase and vibration measurements were compared and the sources of individual noise components were identified.

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10238-13, Session 3

Femtosecond optical parametric amplification in BBO and KTA driven by a Ti:Sapphire laser for LIDT testing and diagnostic development

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We present the design of a collinear femtosecond optical parametric amplification (OPA) system producing a tunable output at wavelengths between 1030 nm and 1080 nm from a pump laser at a wavelength of 795 nm. The pump for this system is a commercial Ti:sapphire chirped pulse amplification laser (Integra-i, Quantronix) that produces 1.65 mJ, 125 fs pulses with a bandwidth of 10 nm and a repetition rate of 1 kHz. A small portion of this pump pulse is first focused into a 5 mm thick sapphire plate to form a single stable filament and generate a supercontinuum seed pulse for the OPA. A 930 nm longpass spectral filter after the sapphire plate then results in a seed with 5 nJ of energy and a spectrum that decays exponentially with increasing wavelength. The first stage of parametric amplification occurs in a Beta Barium Borate (BBO) crystal of

1 mm thickness pumped by the second harmonic of the Ti:sapphire laser. The result is a signal pulse with a nominal energy of 250 nJ and a central wavelength that is tunable through adjustment of the phase matching angle and the relative timing between the pump and the chirped seed pulse.

Two additional stages of amplification in 5 mm thick crystals of Potassium Titanyle Arsenate (KTA) pumped at 795 nm produce a 225 µJ output pulse with a duration of 90 fs. When compared to KTP, the greater transparency of KTA in the spectral range from 3 - 4 µm allows for reduced idler absorption and enhanced gain from the OPA process when it is pumped by the fundamental of the Ti:sapphire laser. The output of the system has been measured by self-referenced spectral interferometry to yield the complete spectrum and spectral phase of the pulse. The use of the Ti:sapphire fundamental at 795 nm as a pump for the second and third amplification stages improves the efficiency with which light can be converted to wavelengths between 1030 nm and 1080 nm and subsequently used to test components for Yb- and Nd-based laser systems. This OPA system is operated for diagnostic development and laser-induced damage threshold testing of optical components for the ELI-Beamlines project.

10238-14, Session 3

Theoretical and experimental study of 808nm OPCPA amplifier by using a DKDP crystal

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The SG II 5PW laser is designed as an open ultra-short high power laser facility in China. Three optical parametric chirped pulse amplification (OPCPA) stages are used to ensure the uncompressed pulse energy up to 260J, which is supported by the largest commercial golden coated grating offered by The JY Company. This laser operates at the center wavelength of 808nm. A four pass zigzag compressor is utilized to compress the laser pulses into less than 30fs@150J per pulse. The beam size of the last OPCPA amplifier is 145mm x 145mm. That means, the nonlinear crystal needed for this amplifier is at least greater than 150mm x 150mm. Since the largest size of the LBO crystal now is no more than 100mm x 100mm. Potassium deuterium phosphate (DKDP) crystal as a candidate has been studied theoretically and experimentally in this report. Phase-matching parameters for various deuterium doped rate DKDP crystals are calculated. OPCPA amplifier based on 95% deuterium doped rate is designed and the output characteristics are simulated by OPA coupled wave equations. Our result shows that DKDP crystals with deuterium doped rate higher than 90% can be utilized in ultra-short high power laser systems with compressed pulses shorter than 30 femtoseconds. Experimental results proved that the output spectrum width is more than 80nm.

10238-34, Session PS

Experimental study on the long-running ablation resistance of new/ gain generators with film cooling for combustion driven DF/HF chemical lasers

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To compact high energy combustion driven DF/HF chemical lasers, an effective method is increasing the total pressure in the combustor, which will result in a favorable high-pressure active medium in the optical cavity for ejecting exhaust components into the ambient atmosphere without gas-jet ejectors. But high combustor total pressure brings about much higher heat flux at nozzle throats, leading to the much easier ablation of nozzle throats, especially in the case of long running. To solve the easy ablation problem of nozzle throats in long running for combustion driven DF/HF chemical lasers, a new gain generator with film cooling was designed. To test the long- running ablation resistance of this new gain generator with film cooling, especially for nozzle throats with large temperature gradient and high heat flux(high combustor total pressure), an ablation resistance experiment platform was built, and a series of ablation experiments from 10s to 60s have been carried out. An observation window was installed at nozzle array, to observe the luminous condition downstream nozzle throats. To evaluate heat loss, temperature sensors were installed to measure cooling water temperature of water-inlet and water-outlet. And to estimate the change of nozzle throat size along with running time, pressure sensors were installed to measure the total pressure in combustor.

According to the relation of flow rate with total pressure P0, total temperature T0 in the combustor and nozzle throat's size A*, when flow rate , T0 and A* keep unchanged, P0 measured in the combustor should not change. But if nozzle throats are ablated, then A* gets larger, and P0 should follow a downward trend.

60s ablation experiment results show that the total pressure in the combustor and fuel total pressures almost kept unchanged in whole running time, indicating the size of nozzle throats kept unchanged and the new gain generator reached a steady state resistant to ablation.

30s experiment results under different heat flux presents that when the total pressure in the combustor increased from 0.3Mpa to 0.36Mpa, the balance time was delayed, but the total pressure in the combustor kept stable after balance, showing that the size of nozzle throats kept unchanged under different high heat flux.

10s ablation experiments show that cooling film in a wide flow rate range, from ~60% to ~100% of full flow rate(~7.5g/s), can protect nozzle throats from ablation effectively

In conclusion, this new film cooling structure can produce stable and consistent cooling film to prevent nozzle throats from ablation, and this new gain generator with film cooling can meet the needs of ablation resistance for high energy combustion driven DF/HF chemical lasers in long running.

10238-35, Session PS

Influence of resonator length on catastrophic optical damage in high-power AlGaInP broad-area lasers

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A variety of applications, such as photodynamic therapy, require efficient red-emitting semiconductor lasers with high output power and continuous wave lifetimes >1000h. AlGaInP lasers have been shown to be the best candidates in this spectral range. However, high-power performance is still limited by major degradation effects, especially catastrophic optical damage. When a laser is driven into higher output powers, the facet regions absorb light, hence making the facets hot, and provoking a "thermal runaway" system and eventually irreversible laser destruction. This effect is called catastrophic optical damage and it is characterized by a sudden drop in the output power at a certain maximum injection current.

The increasing importance of extracting high optical power out of semiconductor lasers motivated several studies in catastrophic optical damage (COD) level improvement. In this study, the influence of the resonator length in high-power broad-area (BA) AlGaInP lasers on COD is presented. In order to analyze the influence of the resonator length on COD, several 638 nm AlGaInP broad area lasers with active width of 60 µm from the same wafer were used. Resonator lengths of 900, 1200, 1500, and 1800 µm were compared. In order to analyze the effect of the resonator length on the maximum power reached by the lasers before COD (PCOD), the lasers used are uncoated and unmounted, and the measurements were done at room temperature under pulsed mode (pulse width: 1 µs, pulse frequency 10 kHz) without any heat-sinking. In this case, COD happens randomly at the front or back facet of the lasers. Pulsed mode instead of continuous mode was used in this analysis to avoid self-heating of the lasers.

It was found that higher output powers and eventually higher PCOD can be achieved using longer resonators; nevertheless, it was also found that this is mainly useful when working at high output powers far away from

the laser threshold, since the laser's threshold current and slope efficiency worsen when the resonator length increases. Moreover, difficulties in mounting long resonators can cause inhomogeneity problems and eventually worse laser performance, so a lot of attention should be paid when mounting the long resonator lasers, which can add more complexities in the manufacturing process. Hence, longer resonators are only advantageous to use when working at high power, far from the threshold current, in order to extract as much power as possible from the lasers.

10238-36, Session PS

Development of few cycle Ti:Sapphire and NOPA amplifiers at 80MHz repetition rate

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Many biological, medical, industrial, and scientific applications demand ultrashort laser pulses both with multi-MHz repetition rate and pulse energy at few tens of nJ. The temporal contrast of high intensity broadband lasers critically depends on the energy of the seed lasers. Combination of both demands motivates us to develop an amplifier system to boost the energy of few cycle laser pulses. The earlier attempts based on CW pump lasers have established a gain of 2-4 [1-2]. The core element of our designs is the recent availability of 80 MHz picosecond lasers [3]. Here we present two operating amplifier systems for few cycle pulses, a NOPA designed to 80 MHz repetition rate, and a cryogenically cooled Ti:S based system at 80 MHz repetition rate, both designed to be tunable between 700-900 nm.

One of the main challenges regarding the MHz repetition rate Ti:S amplifier system is to achieve high overall gain with a pump laser of high average power (15W) but as small pulse energy as half a μJ. Tight focusing is needed to reach the required fluence in the crystal, while such point-like high thermal load calls for cryogenic cooling of the crystal, which is bulky and hence poses a limit on the number of passes of the amplification. To reach a considerably high gain, we modeled, optimized, and experimentally realized a compact, astigmatism-compensated [4] multipass amplifier with tightly focused pump and seed pulses. The beam diameters at each passes were measured with the knife-edge method. Using the novel multipass setup, a total gain of 2.1 was performed after 3 pass at the pump power of 15 W, which can be tuned between the 700-900 nm spectral range.

Regarding the optical parametric amplifier solution, a pilot experiment was carried out to demonstrate the OPCPA design. A conventional CPA system in our laboratory provides 30 fs, 1 mJ pulses at 200 Hz repetition rate. Small fraction of the pulse energy was used to produce a broadband supercontinuum in a piece of BK7 glass, while the remaining part of the IR beam was frequency doubled. The 532 nm part of the continuum was amplified by the second harmonic pulses at 400 nm in an OPA stage, generating 2 μJ pulses at 532 nm. The OPCPA stage based on a 3 mm thick BBO crystal was seeded with the appropriately stretched 800 nm part of the continuum and pumped by the μJ level green pulses. By changing the interaction angle, the wavelength of the amplified pulses was tunable, as expected. We reached the gain factor of 108, which indicates that our amplifier setup is viable. To accomplish the amplification at 80MHz repetition rate the OPCPA will be seeded by broadband pulses of a Ti:S oscillator and pump with the before mentioned μJ level picosecond pump laser.

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10238-37, Session PS

Temperature influence on diode pumped Yb:GGAG laser

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Ytterbium doped solid stated-laser materials have many advantages, especially low thermal load which is essential to high-power, high-energy lasers. A cryogenic cooling can further decrease the thermal load and increase laser efficiency which was demonstrated in many traditional ytterbium doped crystalline laser host materials, like Yb:YAG. A promising alternative to these materials could be mixed garnets. In present study we demonstrate temperature influence (in range from 78 up to 400 K) on spectroscopic properties and laser performance of Yb-doped Gd3GaxAl5-xO12 (Yb:GGAG) crystal. The investigated Yb:GGAG crystal was grown by Czochralski method in a slightly oxidative atmosphere using an iridium crucible. For spectroscopic and laser measurement 2.68 mm thick plane-parallel face-polished Yb:GGAG crystal plate was cut from the grown crystal boule perpendicularly to growth direction (c-axis). The sample was AR coated for pump (930 nm) and generated (1030 nm) laser radiation wavelength. The composition of sample, determined using electron microprobe X-ray elemental analysis, was Gd3.098Yb0.0897Ga2.41Al2.41O12 (3 at. % Yb/Gd). For measurement the Yb:GGAG crystal was mounted in temperature controlled copper holder of the liquid nitrogen cryostat VPF-100 (Janis Research). The absorption spectra were obtained using a spectrophotometer (Shimadzu UV-3600 UV-VIS-NIR, sampling interval 0.05 nm). For laser performance measurement a flat pumping mirror (T > 90 % @ 930 nm, HR @ 1030 nm) was placed inside cryostat and a curved output coupler (curvature radius 150 mm, R=94.5 % @ 1030 nm) was placed outside cryostat. The resonator length was 138 mm. For longitudinal pumping of Yb:GGAG crystal a fiber (core diameter 0.4 mm, NA=0.22) coupled laser diode LIMO60-F400-DI940-FG-E was used. The diode was operating in the pulse regime (5 ms pulse length, 20 Hz repetition rate) at wavelength 928.5 nm. The absorption spectrum of Yb:GGAG crystal was measured for the temperatures from 78 to 400 K. The absorption linewidths narrowed with decreasing temperature. Zero-phonon line at 970 nm has width 1 nm at 100 K. The fluorescence intensity decay time was measured and it increased linearly with temperature from 0.868 ms at 78 K to 0.884 ms at 300 K. Laser performance dependencies were measured for the crystal temperature from 100 to 300 K. The pump wavelength 928.5 nm was chosen to minimize influence of absorption temperature dependence. From the results it follows that the temperature of active medium has strong influence mainly on laser threshold which was 5 times lower at 100 K than at 300 K, and on slope efficiency which was 3 times higher at 100 K than at 300 K. The cryogenic cooling increased the overall efficiency but also complexity of the system.

10238-38, Session PS

Interferometric phase noise measurement of water-cooled mirrors for high average-power femtosecond lasers

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Water cooling of optics and optomechanics is a straightforward solution

in high average power laser systems, where components are exposed to several hundred watts of laser radiation. Steering the beam from the laser to the target area sometimes many tens of meters away, poses severe requirement on mechanical stability. For instance, a laser system utilizing coherent combination [1] requires all the amplifier channels to be "phase-locked" to each other, resulting in a few tens of nanometers maximum path length difference over more than a meter optical path in each channel. Since it is necessary to transport the beam of a high peak power (>TW) laser in vacuum conditions, the requirement of thermal stability adds on the top. The most common solution is the use of water-cooled optical mounts, amplifier stages, and breadboards. Normally laminar flow is favored in these components, since turbulent flow can increase the mechanical vibration (thus group-delay and phase variation) of the optical elements, hence it may deteriorate performance of coherent combination. In this work, we experimentally tested water-cooled mirror mounts made by various manufacturers, which are considered to be built into the beam transport and secondary source beamlines of ELI-ALPS.

The setup was a small Michelson interferometer on a research grade optical table, and included 16 reflections on 1" diameter ultrafast mirrors mounted in the cooled holders. A Ti:Sa oscillator was used as the light source. Vibration of the optical table was measured by an accelerometer (sensitivity of 500 mV/G). We recorded spectrally resolved interferograms [2] with a spectrograph equipped with a high speed Basler spL2048-70km line-scan camera, and used the Fourier-transform method for the evaluation of the spectral phase noise.

Contribution of water flow to the phase noise was negligible below 0.3 l/min, but rapidly increased at higher flow rates. This corresponds to the flow starting to change from laminar to turbulent. (Reynolds number exceeds 2300 at 0.43 l/min for the 4 mm diameter pipes used in the tested mounts, but inner surfaces of pipes are not machined to be absolutely smooth, so flow can easily become turbulent.) When the coolant temperature or flow rate is changed, the group delay keeps slowly changing for a few minutes in the order of 80 fs for the 16 reflections. CEP noise was also extracted from the interferograms, and found to be below 1 mrad RMS.

In conclusion, when using water-cooled optics in applications that need interferometric precision, like coherent combination, one first has to check the flow for turbulence, and wait for the system to reach thermal equilibrium. It can be useful to add a feedback system, which compensates for thermal effects and vibration. After having these conclusions, the mirror mounts were re-designed to be more robust, and at the time of writing, the newly produced mounts are under investigation.

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10238-39, Session PS

6 kW peak power of quasi-CW Yb-doped fiber laser

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Fiber lasers have experienced a more than 20% growth at the macro-material processing industries since a financial crisis of 2008 due to their high efficiency, good beam quality, high compactness and flexibility. High power continuous wave (CW) fiber lasers over several kilowatts have been already commercialized, but the output power from the single fiber laser is limited by nonlinear effects such as a stimulated Raman scattering and a stimulated Brillouin scattering, fiber damages and mode instabilities. To achieve further scaling of the fiber laser output power, coherent, spectral of incoherent combining of laser beams is necessary. In this paper, we constructed four all-fiber laser oscillators based on quasi-CW (QCW) operation. In the macro-material processing, QCW lasers exhibit processability equivalent to CW lasers as well as improvement of the processing quality due to decrement of heat generated in the target. The constructed laser oscillators show a 1.5 kW peak power operated at 10 ms pulse width and 10 Hz repetition rates. The fiber laser outputs from four constructed oscillators were combined through a 4 by 1 signal beam combiner fabricated in house with fiber bundle technique, and 6.0 kW peak power was obtained. The laser performances and characteristics will be reported in detail.

10238-40, Session PS

Diode-side-pumped monolithic Nd:YAG slab laser

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For the purpose of various applications (industry, medicine, military...) a compact all-solid-state high-power and high-energy diode pumped laser systems are requested. The energy limit for these lasers was done primary by the active medium volume, active ions concentration and possibility of pumping. From this reason many concepts of the solid-state active media form were proposed and experimentally investigated. Goal of our work was development and construction of compact, side-pumped monolithic laser based on Nd:YAG slab crystal with an internal ring cavity. A horizontal projection of the active medium form was a isosceles trapezoid with 18.6 mm long base, and 5 mm height. The angels between long base and legs are 87 deg. The thickness of the slab was 4 mm. Both base-sides and one leg-side was high reflective for lasing radiation. Second leg-side was partially reflective for lasing radiation and serves as an output coupler. In our experiments we used Fresnel reflections form this un-coated face. The longer base-side was highly transparent for pumping radiation. The opposite, shorter base-side, was highly reflecting for pump radiation and serves for pumping recycling. To increase the pump absorption efficiency Nd-doping concentration was 1.4 % Nd/Y. The designed active crystal shape ensures four internal reflections of generated laser radiation forming a ring resonator with high gain. As a pump source, a linear single-bar quasi-cw fast-axis collimated laser diode JOLD-180-QPFN (Jenoptik) with peak power 180 W was used. The diode was mounted on the copper plate with Peltier cooling which enables fine tuning of the generated radiation wavelength around 808 nm to match the Nd:YAG absorption peak. The laser diode output beam without any further optics was used for slab side-pumping. The diameter of the pumping beam in the vertical axis was 0.9 mm. The width of pumping area was 10 mm. The pumping pulses with repetition rate 5 Hz were 200 us long. The maximum pumping energy was 39 mJ. The Nd:YAG laser was operated for most known Nd3+ ion transition 4F3/2 ® 4I11/2 which leads to the emission at 1.06 mm. Two external mirrors (one totally reflecting for laser emission, second with reflectivity 80 % at 1.06 mm) were used to increase the feedback and to form the oscillator. The total footprint of the laser system including the pumping diode was 10 x 10 cm2. The laser was tested in the free-running regime. The maximum laser output energy reached was 5.9 mJ which corresponds to optical-to-optical efficiency of 15 %. The laser slope efficiency in respect to laser diode output was 20 %. The divergence of multimode output beam was 7 x 2.5 mrad. We believe that optimizing the output coupler reflectivity and its deposition directly on slab face will even improve overall efficiency and compactness of the system.

10238-41, Session PS

Development of 2.7-μm Er:Y2O3 ceramic laser operated at room temperature

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Erbium-based lasers operating in the 2.7-3.0 μm spectral range are attractive for multiple applications, including molecular spectroscopy and remote sensing, laser surgery and optical pumping of mid-IR laser sources. These active materials can be pumped directly to the upper laser level at 0.97-0.98 μm, using the 4I15/2 ? 4I11/2 pump transition and 4I11/2 ? 4I13/2 laser transition. A disadvantage of this laser operation scheme is a high quantum defect of about 65%, which imposes generation of large amount of heat in the active medium and thus impedes scaling of output power. Therefore, high thermal conductivity of the host material is necessary for high-average-power laser generation. Furthermore, the upper-state lifetime at room temperature is for Er-doped media operating around 3-μm several times shorter than the lifetime of the lower laser level. It is therefore essential to utilize the concentration-dependent upconversion process which depletes the population of the lower laser level and enables continuous-wave (CW) and high-duty-cycle pulsed operation. To maximize the upper-state lifetime, low phonon energy of the laser material is needed. For these reasons, the Er:Y2O3 shows great promise thanks to its superior thermal conductivity and one of the lowest maximum phonon energies among Er-doped gain materials. In this work, we investigated laser properties and performance of Er:Y2O3 at room temperature.

For our experiment, we have used 15 at.% Er:Y2O3 ceramics fabricated by Konoshima Chemical Co., Ltd. Due to complex energy level structure of the Er:Y2O3, the pump wavelength has to be chosen carefully. To assess this matter, we measured absorption spectra of Er:Y2O3 near 1 μm at room temperature and also for lower temperatures down to 80 K.

The ceramic sample used for lasing was 10 mm long with clear aperture of 2?5 mm2, with one face AR-coated for both laser and pump wavelength and dichroic second face with HR/AR coating for laser/pump wavelength. As a pump source we used a broadband 976-nm, 60-W laser diode with wavelength tuned down to 971 nm. The laser cavity was plane-parallel with the output-coupling mirror placed just next to the AR-coated face of the laser ceramics – we utilized strong thermal lensing in the ceramics to ensure stability of the resonator. Reflectance of the output coupler for the best performance was 95.5%.

With this setup, we achieved lasing at room temperature in quasi-CW regime. The CW operation was restricted by amount of heat generated in the water-cooled ceramics under continuous pumping. This prevented reaching the laser threshold without overheating the crystal. In quasi-CW operation with duty cycle of 1%, output power amplitude of 1.01 W (500 μs pulses, average power 10.1 mW, slope efficiency 3%) was achieved. By increasing pulse repetition rate from 20 Hz to 70 Hz, up to 26 mW at 2.7 μm was obtained.

Further work should be focused on increasing the overall efficiency and limiting the residual heat generation. This can be achieved by optimizing the doping concentration of the ceramics and using a narrowband pump diode of suitable wavelength, effectively limiting the unwanted excited-state absorption and upconversion from the upper laser level.

10238-42, Session PS

Preliminary simulation results of the ESA QOMA II project: A new DPSS conductively cooled, passively Q-Switched laser source suitable for space applications

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In the frame of the ESA project QOMA I (Q-Switched Master Oscillator based on Multidoping Nd:YAG Technology for Optoelectronics Space Applications) a high-power, low cost, low weight, low length Q-switched Master Oscillator component suitable for space lidar applications in ESA or any other agency missions was designed, developed and breadboard tested. The implemented laser was an actively Q-Switched Nd:YAG laser, end pumped directly to the upper laser state (885 nm) by a diode laser source. Moreover, a multisegmented Nd:YAG crystal was used in order to reduce thermal lensing effects and mechanical stresses inside the Nd:YAG crystal. The implemented laser was water cooled and produced pulses of 2.6 mJ at 1 kHz with pulse duration 22 ns. The spatial beam profile was M2=1.3. [Tsaknakis et al., 2013], [Evangelatos et al., 2013 and 2014].

In this work we present simulation results performed in the frame of QOMA II project, also funded by the European Space Agency. The purpose of QOMA II is to scale up the implemented laser during QOMA I, to produce laser pulses with energy higher than 10 mJ, and pulse duration lower than 15 ns @ 100 Hz repetition frequency, with M2<1.2. The same pumping configuration as in QOMA I will be employed [i.e. end pumping of multisegmented Nd:YAG rods directly to the upper laser state (885 nm)]. In QOMA II the laser will be conductively cooled and passively Q-Switched.

In order to achieve the program objectives we performed simulations using the advanced laser design software LASCAD© and OXALIS© along with Zemax© optical design software in order to calculate the required pump diode laser specifications, along with the optimum laser cavity geometry, for maximun output energy. No waveguiding inside the crystal was present according to Zemax. Moreover, the multisegmented crystal geometric and doping specifications were also calculated in order to maximize the pump power absorption and minimize the thermal lensing and mechanichal distortion effects inside the crystal. The simulation results showed that laser energies per pulse around 15mJ could be achieved, although this could be considered as an optimistic value. As far as the laser beam quality is concerned, our simulations showed that further work should be done concerning the laser cavity geometry in order to meet the project's requirements.

10238-43, Session PS

LIDT test station for optical elements testing under cryogenic conditions

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In this contribution we present a technology for deposition and testing of interference coatings for optical components designed to operate in power pulsed lasers. The aim of our efforts is to be able to produce coatings and test their suitability for use in high power laser facilities such as ELI (Extreme Light Infrastructure) or HiLASE. The choice of the material for the lasers' optical components 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. As large amounts of heat need to be dissipated during laser operation, cryogenic cooling is necessary. We designed and built a LIDT test station 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. Multiple test sites on the sample's surface were used for different laser pulse energies. We used optical and electron microscopy to inspect the coatings before and after the conducted experiments. The obtained information was used to optimize the optical coating designs which are used by our SYRUSpro 710 coating system. Also spectrophotometric measurements were conducted to determine the temperature dependence of refractive indices of the materials used during the coating production process.

10238-44, Session PS

Room temperature CW and QCW operation of Ho:CaF2 laser pumped by Tm:fiber laser

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Laser radiation in the wavelength range around 2 um is required for its specific properties – because of its strong absorption in water and tissue, it is very suitable for medical applications. There are also absorption bands of various atmospheric gases and this radiation can therefore be used for remote sensing. Optical parametric oscillators based on highly-nonlinear crystals pumped by 2 um radiation can be used to generate ultrafast pulses in the mid-IR region further exploited in nonlinear optics.

Crystals as YLF, YAG, LLF, and GdVO4 doped by holmium were already investigated thoroughly and found suitable for the tunable laser generation around 2.1 um. These systems were usually pumped by Tm-doped fiber or bulk solid-state lasers matching the holmium absorption band around 1.94 um. On the other hand, only a few works are devoted to the laser operation of holmium-doped fluorides as CaF2. Ho:CaF2 laser operation at liquid nitrogen temperature was demonstrated recently. In this work, pulsed and continuous-wave laser operation of a modified-Bridgman-grown Ho:CaF2 active crystal at room temperature pumped by Tm:fiber laser is reported.

A commercial Tm-fiber laser generating the maximum output power of 50 W at the wavelength of 1940 nm was used as a pump source and the radiation was focused into the Ho:CaF2 active crystal. The novel 0.5 at.% Ho:CaF2 active crystal had the dimensions of 10 x 3 x 3 mm and it was Peltier-cooled to 16 degC. The stable optical resonator was formed by a flat pumping mirror (T = 99 % at 1940 nm & R > 99 % at 2050-2150 nm) and a concave output coupler with various reflectivity (R = 90 to 98 % around 2100 nm).

In the pulsed regime (t =?10 ms, f = 10 Hz), the maximum mean output power of 310 mW (corresponding to power amplitude of 3.1 W) was achieved together with the slope efficiency of 21% with respect to the pump power incident on the crystal input face. Because of low single pass absorption of 0.3, the slope efficiency of 69% with respect to the absorbed pump power can be calculated. This value can be considered as the highest estimation because some part of the pumping radiation transmitted through the active crystal can be reflected from the output coupler back to the active crystal and improve the pumping efficiency. The Ho:CaF2 laser generated around the wavelength of 2100 nm.

Stable continuous-wave Ho:CaF2 laser operation was also achieved with the maximum mean power of 740 mW and slope efficiency of 13% with respect to the incident pump power and efficiency of 41% with respect to the absorbed pump power.

The Ho:CaF2 laser output wavelength tuning possibilities were also investigated. Using a birefringent filter, continuously-tunable generation in the wavelength range 2034-2120 nm with the maximum around 2100 nm at room temperature was demonstrated.

10238-45, Session PS

Precision control of mirror-grating phasing for a laser pulse compressor

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Tiled-grating compressors of ultra-short pulse multi-petawatt lasers are currently the only viable way how to meet beam size requirements and stay within the damage threshold of the largest available multilayer dielectric gratings. Recently, a method how to double the effective aperture of compressor gratings by phasing them with perpendicularly positioned mirrors has been proposed providing a simplification to the traditional grating-grating tiling scheme by reducing the number of alignment degrees of freedom. The drawback of the method lies in tighter requirements on adjustment precision and stability of the system making the alignment and monitoring a challenging task. Here we propose and analyze different approaches to the precision control of mirror-grating phasing and present a comparative experimental verification of the alignment systems on a small-scale test bench.

10238-46, Session PS

InAs/GaSb superlattice photodiode array pixel isolation by fs laser annealed band gap blue-shift of the inter-pixel regions

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Mid wave infrared (MWIR) and long wave infrared (LWIR) focal plane arrays (FPAs) are essential for thermal imaging in military and civil applications. Recently, FPAs based on InAs/GaSb superlattices (SLs), of type-II band alignment, has rapidly advanced [1]. However, some primary technological issues governing the degree of integration in small pixel size large format FPAs, still exist. One primary constraint of mesa etched SL FPAs is the occurrence of high mesa sidewall surface leakage current, arising from dangling bonds and conductive oxides at the surface of the mesa sidewalls. To eliminate this effect, a large number of surface passivation techniques have been demonstrated. However, these passivation methods either suffer from issues with long term stability or complicates the FPA fabrication process.

Recently, we reported [2] a method for pixel isolation in MWIR InAs/GaSb SL photodiode arrays, without the conventional mesa etching, of a 775 nm fs laser anneal technique. The basic idea of this technique is to isolate the pixels by forming a higher band gap SL material from that of the as-grown SL, by layer intermixing in the interpixel regions. The p-i-n SL layer structure is designed for operating at wavelengths of ~ 3-5.5μm. The fabrication processes starts with the formation of pixels areas covered with Ti/Au photomasks and a subsequent p+ layer dry etch of the inter-pixel regions. fs laser pulses then irradiates this p+ etched SL structure from the top surface, to selectively laser anneal the inter-pixel regions. The low temperature current-voltage measurements of these laser annealed photodiodes shows a two-fold improvement in the inter-pixel isolation, as compared to that with unannealed SL diodes. A variable-area diode array (VADA) technique also showed a seven fold reduction in the surface component of the dark current in the fs laser annealed diodes over un-passivated conventional mesa etched photodiode arrays.

In this work, we report the confirmation of our proposed laser induced layer intermixing to be the reason for this inter-pixel isolation. Optical measurements using Fourier Transform Infrared (FTIR) spectroscopy to estimate the shifts in the SL band gap of the laser annealed inter-pixel regions from that of the masked pixel area, is presented. In the laser annealed pixel or photodiode regions, the SL peaks are clearly visible with nearly equal absorbance values as that of the as-grown SL. Additionally, there is negligible shift in the band gap of the pixel regions which, as expected, ensures that the SL quality in the active photodiode regions is hardly affected after the anneal process. On the other hand, FTIR result shows a large band gap blue-shift of ~ 70 meV in the inter-pixel regions. This band gap blue-shifted inter-pixel region provides a barrier between the pixels, thus accounting for the improvement in the pixels isolation.

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10238-15, Session 4

Intracavity stretcher for high-power chirped-pulse amplification *(Invited Paper)*

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Since the introduction of chirped-pulse amplification (CPA), where the

pulses are temporally stretched, then amplified and finally recompressed, short pulse, high-energy laser systems have become an important tool for a great variety of laser-matter interaction experiments. Several laser systems using the CPA-technique aiming for Petawatt peak powers are operational or currently under development worldwide [1]. Such systems usually use large diffraction gratings (half-meter scale) and reflection telescopes with optics having diameters of several inches to stretch the pulses to nanosecond durations. The pulse compressors likewise comprise several meter-scale diffraction gratings. To achieve high-quality pulses (with respect to intensity contrast) after recompression these optics and in particular the stretcher telescopes have to exhibit extreme low surface roughness and high flatness (c.f. [2] for the influence on the pulse contrast), which next to their pure size makes these optics extremely expensive.

By using prisms [3] or single gratings [4] within regenerative amplifiers it has been shown that the pulses can be stretched without the use of large stretcher setups. Here the pulses are stretched by a small amount during each cavity round-trip and therefore the stretcher itself is comparably compact. However, these setups have so far demonstrated stretching factors of a few ps per round-trip only and are therefore not suitable for high-power laser systems requiring stretched pulses with ns duration.

We present a newly developed design using an Offner-type stretcher, consisting of a diffraction grating, a reflective telescope and a roof prism, within a regenerative amplifier. The design of this stretching-amplifier (StAmp) allows the pulses to be stretched to ns-durations within a reasonable number of 40 round-trips in which the pulses are simultaneously amplified to 100 μJ energy. The distance between telescope and grating is tunable and the StAmp can either be used for tuning the dispersion after the compression stage or for changing the stretched pulse duration from femto- to nanoseconds. By using spectral filters to compensate for gain narrowing the spectral width of the output pulses is 27 nm (FWHM). The pulses stretched by the StAmp where used as the seed for the high-power laser system POLARIS. The fully amplified pulses have been recompressed to durations as short as 102 fs reaching 100 TW peak powers. We investigated the temporal intensity contrast in the ps- and ns-regime and demonstrate that by applying the StAmp to the POLARIS system the relative intensity level of the amplified spontaneous emission was reduced by a factor of 4 to 1.6?10-13. Our results demonstrate that our intracavity design is a promising stretcher technique for high-energy, short-pulse laser systems.

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10238-16, Session 4

Commissioning of a kW-class nanosecond pulsed DPSSL operating at 105 J, 10 Hz *(Invited Paper)*

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For more than a decade development of high-energy diode pumped solid state lasers (DPSSLs) has focused on scaling energy and increasing pulse repetition rate to unlock their potential for practical applications. These include new sources for industrial materials processing applications and as pump sources for higher repetition rate PW-class amplifiers, which can themselves generate high-brightness secondary radiation and ion sources leading to new remote imaging and medical applications.

Over recent years, the DiPOLE team within the Centre for Advanced Laser Technology and Applications (CALTA), part of the Central Laser Facility (CLF), has been developing a 100J-class nanosecond pulsed DPSSL based on scalable cryogenic gas cooled, multi-slab ceramic Yb:YAG amplifier technology [1] capable of operating at 10 Hz pulse rates. Design and build of the first system in the UK, DiPOLE100 [2], was funded by the HiLASE project [3] in the Czech Republic to demonstrate the potential of high-energy DPSSL technology for industrial applications. Construction began in April 2013 and was completed by October 2015. The potential of DiPOLE100 was confirmed during preliminary testing where 10 ns duration pulses at 1029.5 nm were amplified to energies in excess of 100 J at 1 Hz [4]. Over the following 12 months, the system was packaged, shipped, reassembled and recommissioned at the HiLASE Centre by a team from the CLF and HiLASE.

In this paper we present performance results from the final stage of commissioning DiPOLE100 at the end of 2016. This culminated in the successful demonstration of the world’s first kW average power, high-energy, nanosecond pulsed DPSSL. The first long-term test for amplification of 10 ns duration pulses at 10 Hz pulse repetition rate demonstrated an output energy of over 100 J for an hour, corresponding to over 38,000 pulses, with an average energy of 105 J and RMS energy stability of approximately 1%. This was achieved at a pump energy of 465 J, corresponding to an optical-to-optical conversion efficiency of 22.5%, and an operating temperature of 150K. Further details of commissioning and system performance will be presented along with plans for future system development.

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10238-17, Session 4

Active cavity stabilization for high-energy thin disk regenerative amplifier

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ELI – Beamlines, based in the Czech Republic, is a European project aiming to commission multiple high-power, ultrafast laser beamlines. The first beamline (L1) consists of a high repetition rate OPCPA (Optical Parametric Chirped Pulse Amplifier) with design output parameters of 100 mJ at 1 kHz and < 20 fs pulse duration with a center wavelength of 825 nm. After completion, this system will be used for the generation of high-brilliance X-ray sources for users in biophysics, material science, and molecular science. Designed for user operation, the highest requirements towards stability and reliability are imposed onto the system.

The OPCPA is pumped by picosecond pulses generated from Yb:YAG thin disk amplifier systems. The first four stages are pumped by a 30 mJ and a 100 mJ home build regenerative amplifier (RA), stages five and six by two commercial 230 mJ RAs (Dira 200-1, Trumpf Scientific). The seventh and final stage is pumped by a still to be developed RA and multipass amplifier combination.

Here, we report on the development of an active cavity stabilization system implemented into the 230 mJ RA system. Traditionally, pointing stabilization systems track the position of the beam from the leakage of a mirror. Now, instead, we retrieve the position of the beam directly from the thin disk gain crystal, where the overlap between pump and seed is most crucial, by monitoring the area depleted by the cavity mode within the pump spot. When pumping the thin disk gain medium, the excited ions emit fluorescence, which is imaged onto a camera.

In presence of the seed, one can clearly see the overlap of the pump with the seed by observing the intensity dip within the pumped area. In most cases, this image is used for damage inspection and manual alignment only. By recording a single calibration image of the unseeded disk, without dip, and subtracting from this image the current seeded disk image, with dip, one obtains an image directly showing the cavity mode as a beam like feature. From this image the seed position on the disk is determined by means of center of gravity calculations. The position on the disk is then fed back to one of the piezo mounts in the cavity.

The position on the disk is then fed back to one of the piezo mounts in the cavity. By adding the cavity stabilization, the laser becomes a truly hands-off system that runs stable and reliable right from the start and throughout the whole day. The power and pointing remain stable whether the system is exposed to changes in lab temperatures, or whether it undergoes a complete cold start and even an emergency shutoff and restart. Interestingly, the stabilization works for different power settings, for example 100 W and 230 W, despite using the same calibration image recorded at 100 W. Furthermore, the feedback loop, running at 20 Hz, significantly reduces fast fluctuations, caused by air turbulences, which become particularly troublesome when running the laser at full power at 230 W. A thorough quantitative analysis of the performance of the stabilization system will be presented.

10238-18, Session 4

Latest developments on fibered MOPA in mJ range with hollow-core fiber beam delivery and fiber beam shaping used as seeder for large scale laser facilities

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The Laser Megajoule (LMJ) is a French large scale laser facility dedicated to inertial fusion and plasma physics research. LMJ front-ends are based on fiber laser technology at nanojoule range [1]. Scaling the energy of those fiber seeders to the millijoule range is a way to upgrade LMJ's front ends architecture and could also be used as seeder for lasers for ELI project for example. However, required performances are so restrictive (optical-signal-to-noise ratio higher than 50 dB, temporally-shaped nanosecond pulses and spatial single-mode top-hat beam output) that such fiber systems are very tricky to build.

High-energy fiber amplifiers

In 2015, we have demonstrated, an all-fiber MOPA prototype able to produce a millijoule seeder, but unfortunately not 100% conform for all LMJ's performances. A major difficulty was to manage the frequency modulation used to avoid stimulated Brillouin scattering, to amplitude modulation (FM-AM) conversion, this limits the energy at 170µJ.

For upgrading the energy to the millijoule range, it's necessary to use an amplifier with a larger core fiber. However, this fiber must still be flexible; polarization maintaining and exhibit a strictly single-mode behaviour. We are thus developing a new amplifier architecture based on an Yb-doped tapered fiber: its core diameter is from a narrow input to a wide output (MFD 8 to 26 µm). A S? measurement on a 2,5m long tapered fiber rolled-up on 22 cm diameter confirmed that this original geometry allows obtaining strictly single-mode behaviour. In a 1 kHz repetition rate regime, we already obtain 750 µJ pulses, and we are on the way to mJ, respecting LMJ performances.

Beam delivery

In LMJ architecture the distance between the nanojoule fiber seeder and the amplifier stages is about 16 m. Beam delivery is achieved with a standard PM fiber, such a solution is no longer achievable with hundreds of kilowatt peak powers. An efficient way to minimize nonlinear effects is to use hollow-core (HC) fibers. The comparison between the different fibers will be presented in the conference.

Fiber spatial beam shaping

Spatial beam shaping (top-hat profile) is mandatory to optimize the energy extraction in free-space amplifier. It would be very interesting to obtain a flat-top beam in an all-fiber way. Accordingly, we have design and realize a large mode area single-mode top-hat fiber able to deliver a coherent top-hat beam. This fiber, with larger MFD adapted to mJ pulse, will be implemented to perform the spatial beam shaping from coherent Gaussian profile to coherent top-hat intensity profile in the mJ range. In conclusion, we will present an all-fiber MOPA built to fulfil stringent requirements for large scale laser facility seeding. We have already achieved 750 µJ with 10 ns square pulses. Transport of high peak power pulses over 17 m in a hollow-core fiber has been achieved and points out FM to AM conversion management issues. Moreover, spatial beam shaping is obtained by using specifically designed single-mode fibers. Various optimizations are currently under progress and will be presented.

10238-47, Session 4

High-beam quality, all-solid-state 1000 W nanosecond Nd:YAG laser system *(Invited Paper)*

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In this paper, we develop a diode-pumped all-solid-state Nd:YAG laser system with high beam quality. The laser system is constructed in a master oscillator power amplifier (MOPA) configuration, with four components: a single-frequency seed laser, pre-amplifier unit, beam control unit, and post-amplifier unit. The single-frequency seed laser produces an output power of 9.1 ?J with a pulse duration of 35.3 ns (FWHM) at 200 Hz repetition rate. The root-mean-square (RMS) fluctuation in pulse energy is smaller than 1% and the beam quality is better than 1.13 times diffraction limited (DL). The pre-amplifier consists of a three-stage side-pumped rod amplifier. The stimulated Brillouin scattering phase-conjugate mirror (SBS-PCM) technique is implemented in the control unit to correct the wavefront distortion dynamically. The post-amplifier unit is composed of a three-stage large slab amplifier. And an adaptive optics system is applied for wavefront correction at the end of the system. A 1.6 times diffraction limited (DL) output beam with a pulse energy of 5 J at 1064 nm is first-ever achieved with a pulse duration of 8.7 ns at a repetition rate of 200 Hz, and the output energy stability is 5.6% peak-to-valley.

10238-19, Session 5

Gigawatt mid-IR (4-5 μm) femtosecond amplifier of OPA seed pulse in monocrystalline Fe2+:ZnSe optically pumped by solid-state 3 μm laser *(Invited Paper)*

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The efficient amplification of the broadband tunable (from 3.8 μm up to 4.8 μm) mid-IR femtosecond (~200 fs) seed pulse in optically pumped Fe2+:ZnSe amplifier have been demonstrated for the first time in air and in nobble gas. Gain evolution measurements have shown that the lifetime of population inversion of Fe2+:ZnSe strongly depends on the temperature. It increases from 350 ns (at room temperature) up to 1 μs (at 7 degrees Celsius) paving the way for multi-pass amplification. As a result, femtosecond seed radiation centered at 4.3 μm was amplified in six-pass Fe2+:ZnSe amplifier with the total gain of about 2000 and peak power up to 0.5 GW. Substitution of air by argon removes spectral distortions in the laser pulse caused by the absorption by atmospheric CO2 molecules. It does not radically improve the amplification process in Fe2+:ZnSe but stabilizes the operating regime. Our further efforts and improvements of this mid-IR femtosecond laser source will be directed towards the intensity contrast cleaning and the creation of the grating based stretcher and compressor in order to prevent self-phase modulation and beam collapse during the amplification process in Fe2+:ZnSe. This procedure paves the way for increase of the output peak power up to 10-20 GW with the pump pulse energy from 30 to 60 mJ and the pump energy fluence kept at 0.6 J/cm2 in the 2.5-3.6 mm spot size respectively.

Finally, we can add that the designed scheme can be modified in order to significantly enhance output energy to reach subterawatt power level with output energy of about 6 mJ and pulse duration of tens of femtoseconds. It should be noted, that modern commercial parametric amplifiers, like TOPAS, for instance, by Coherent Inc., has more than 8 μJ energy for a 4 μm wavelength and less than 130 fs pulse duration. At relatively low saturation fluence of about 40 mJ/cm2 the output energy is strongly determined by both the length and cross section of the active element. In addition, high energy pump should be used. In order to suppress the radiation losses in the direction orthogonal to the optical axis the beam diameter should be less than the gain medium length. In our case, it is reasonable to keep it at 5 mm. The pump laser should provide 120 mJ energy in order to keep laser energy density at a level of 0.6 J/cm^2. This was achieved by us. Thus, the output energy extracted from the multipass Fe2+:ZnSe amplifier expected to be about 12 mJ for these initial conditions. The use of non-linear compressor operating in the regime of anomalous dispersion group velocity (3-fold pulse self-compression is possible, for example, using CaF2 crystal) will allow to obtain an output power of about 0.2TW with a two-cycle pulse duration.

10238-20, Session 5

Temperature dependent spectroscopic characterization of Tm:YAG and Tm:YAP crystals as potential laser media for pulsed high-energy laser amplifiers

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Laser materials doped with trivalent thulium ions have recently attracted attention for their application in diode pumped solid state lasers. These laser materials operate at laser wavelengths between 1.8 μm and 2 μm while readily available high power laser diodes emitting around 800 nm can be used for pumping. Due to the cross relaxation process allowing for a quantum efficiency of up to 2, a low quantum defect between 10 and 20% can be obtained despite the large separation between pump and laser wavelength. Furthermore, due to the very long radiative lifetime, which is about ten times higher than in ytterbium doped materials, it is possible to transfer a lot of energy into the laser medium even at rather low pump powers suggesting a very high potential for their application in high energy class lasers, since the pump engine required to achieve the same output energy could be significantly smaller.

Similar to ytterbium doped laser materials thulium doped media are normally operated within a quasi three level scheme, which especially for pulse pumped lasers is a significant drawback for efficient laser operation, as a significant amount of energy is required to bleach out the laser medium. Since this energy cannot be extracted, it is lost for the amplification. Hence, operation of such lasers at cryogenic temperatures seems an appropriate solution. For further modeling and derivation of design rules for future laser systems based on such a scheme reliable spectral data is needed. We will present absorption and emission measurements on Tm:YAG and Tm:YAP in dependence of temperature in the range from 80K to 300K covering both the absorption bands around 800 nm and the emission bands up to 2μm. The spectral measurements were carried out for a Tm:YAP crystal with 8 at.% doping in all three crystal axis and two samples of Tm:YAG with doping levels of 2 at.% and 8 at.%. Precautions for reabsorption effects were taken to allow for accurate results over the whole measurement range. From these measurements we derived absorption and emission cross sections and radiative lifetimes. By comparing the latter values to values obtained by highly accurate measurements of the lifetime using the pinhole method we also estimated the quantum efficiency.

10238-21, Session 5

Pump-induced phase aberrations in Yb3+-doped materials

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Optical pumping of laser materials is an effective way to create a population inversion necessary for laser operation. However, a fraction of the pump energy is always transfered as heat into the laser material, which is mainly caused by the quantum defect. For Yb3+-doped materials, the small energy difference between the pump level and the laser level and the pumping with narrowband high-power laser diodes result in a quantum defect of approx. 9%, which is significantly lower compared to other dopants e.g. Ti3+ (33%) or Nd3+ (24%). Due to the low heat introduction, high optical-to-optical efficiency and high repetition rate laser systems based on diode-pumping are well-suited for a number of applications. Here, however, laser beam quality is of crucial importance. Phase distortions and beam profile modulations can lead to optical damages as well as a significant reduction of the focal spot intensity.

Pump-induced phase aberrations are the main cause for phase distortions of the amplified laser beam. The heat transferred to the material causes a change of the refractive index (dn/dT), thermal expansion and stress within the laser material, eventually leading to spatial phase aberrations (also called 'thermal lens'). However, the spatially dependent distribution

of the population inversion itself also leads to spatial phase aberrations. Since electron excitation directly leads to a change in the charge distribution of the laser active ions, the dynamic response of the material to external fields changes. These electronic phase aberrations (also called 'population lens') are described by a change in the polarizability of the material. Due to the low quantum defect of Yb3+-doped materials, this effect becomes more important.

We show the first comprehensive spatio-temporal characterization of the pump-induced phase aberration including both effects. A high-resolution interference measurement was carried out with time steps of 50µs for times during the pump period and the cooling period between subsequent pump pulses. We found that both phase effects significantly contribute to the overall phase distortions. Since the temporal characteristic of the electronic phase depends on the fluorescence lifetime and the thermal phase on the thermal diffusivity, both phase effects could be distinguished by their different lifetimes. The measurements were carried out for Yb:YAG, Yb:CaF2 and Yb:glass, and are in excellent agreement to our detailed, COMSOL-based, spatio-temporal phase simulations. Since Yb:CaF2 and Yb:glass provide a negative dn/dT, the electronic phase change becomes even more important and, in case of Yb:CaF2, almost completely compensates the thermal phase imprint of a pump pulse during the time frame of laser pulse amplification.

10238-22, Session 5

Wavefront aberration measurement in a cryogenically cooled Yb:YAG slab using a wavefront sensor

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High energy laser systems with pulse duration of a few picoseconds and a good beam quality factor (M2) providing high-intensity at focal spots are required for a number of applications in industry and science. Currently, Yb:YAG crystal is a widely used active medium at room temperature due to its good thermo-optic properties, long upper state lifetime, low quantum defect and broad gain bandwidth. However, at room temperatures, high saturation fluence makes it difficult to efficiently extract stored energy in the Yb:YAG crystal with a low number of passes through the gain medium resulting in a degradation of the wavefront quality. Therefore, to enhance the energy scalability and maintain near diffraction-limited beam quality, cryogenic technology is required.

We investigated wavefront aberrations in a cryogenically cooled Yb:YAG slab with a wavefront sensor using a probe beam technique at non lasing condition. To analyze the aberration induced by the crystal, the measured wavefronts were fitted with orthonormal Zernike polynomials. The Yb:YAG crystal of 2 mm thickness, 10 mm diameter, and 3 at.% doping concentration was mounted in a copper holder in a closed-loop pulse tube cryostat with cooling capacity of 12 W at 100 K. The gain medium was single-end pumped by a fiber-coupled laser diode at pumping intensity of ~6.3 kW/cm2 with a maximum repetition rate of 100 Hz, pulse duration of 1 ms, and pump spot diameter of 2.5 mm. The time resolved measurement revealed that defocus, which was the main wavefront aberration, represents not only a thermal lensing effect but also an electronic lensing effect. The thermally induced defocus is more dominant at high repetition rate than electronically induced defocus. However, at relatively low repetition rate operated laser systems with high pumping intensity, electronic lensing can be comparable or even higher than the thermally induced lens effect.

In addition, we measured wavefront aberrations of amplified beams in a cryogenically cooled Yb:YAG slab. A room temperature operated thin-disk regenerative amplifier was used as a seed laser. The seed beam was amplified in the cryogenically cooled crystal at 160 K in double pass configuration. The wavefront measurement was conducted at semi-saturation conditions at three different repetition rates: 10, 20, and 40 Hz and at five different pump intensities in the range between 6.5 and 14.8 kW/cm2. Under lasing condition, similarly to non-lasing condition, only defocus and spherical aberration were induced. At repetition rate of 40 Hz and pumping intensity of 14.8 kW/cm2, the defocus and spherical aberrations were 40 nm (<0.04 ?) and ? 20 nm (? 0.02 ?), respectively. We found that the negative spherical aberration induced by the cryogenically cooled Yb:YAG crystal partly compensates the positive spherical wavefront aberration of the seed beam resulting in a higher Strehl ratio of the amplified beam compared to input beam. We also measured saturation curve of the amplifier. Overview of the most important results crucial for cryogenically cooled slab laser design will be presented.

10238-23, Session 5

Investigation and modelling of pump saturation effect on thermal load of Yb:YAG thin disk pumped at various wavelengths

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To the major heat source in laser gain media belongs a quantum defect, i.e. heat produced by non-radiative transitions during transformation of pump photons with higher energy to signal photons with lower energy. Although in case of diode pumped Yb:YAG lasers is the quantum defect small, pumping of high average power Yb:YAG thin disk-based lasers at high pump intensities causes strong warming up of the thin disk active media, which is usually followed by mechanical deformation of the disk. This leads to a detrimental effect on achievement of high output powers. Amount of generated heat can be effectively reduced by pumping directly to upper laser level (so called zero phonon line pumping), which corresponds to 969 nm in Yb:YAG. However, we found that heat reduction after employment of the zero phonon line pumping cannot be attributed only to the lowering of the quantum defect. We therefore investigated further relations between disk temperature, absorption of the pump beam, and laser output power in real-time experiment with a goal to optimize laser design and to improve agreement between experimental data and theoretical modelling of disk lasers both for the zero phonon line pumping and the conventional pumping at 940 nm.

Real-time-measurement of pump wavelength effect on the laser operation was done by a V-cavity laser using 220um thick Yb:YAG thin disk cooled by a water nozzle from the back side. Pump beam diameter was 2.8mm. A non-absorbed pump power and laser output power were measured simultaneously as well as disk surface temperature, which was evaluated by a thermal camera placed directly in front of the disk. The disk was pumped by a high power diode at 940 nm or by a narrow band diode at zero-phonon line (969 nm) without changing a cavity setup. The CW pump power was gradually changed from 100 W to 400 W. Experiment was realized in non-lasing as well as in lasing regime. Based on measured data, absorption was evaluated including experimentally measured losses in disk head.

In case of zero phonon line pumping saturation of absorption at significantly lower level was observed than saturation intensity expected from the value calculated from spectroscopically measured absorption cross section at given pump wavelength and temperature. The difference is significant for both the pump wavelengths. Also differences in absorptions for lasing and non-lasing regimes at both the pump wavelengths were observed. Following update of the thermal thin disk model by the measured absorption data improved accuracy and agreement between the experimental and theoretical data of the disk surface temperature significantly. Prediction of the model corresponds now to reality very well in broad range of pump intensities.

Results of the experiment as well as details of the thermal modelling including comparison of theoretical and experimental data will be presented. We also expect results from improved spectrally resolved measurement of all data up to pump power of 1 kW and comparison with the theoretical model by the time of the conference.

10238-24, Session 6

Design update and recent results of the Apollon 10 PW facility *(Invited Paper)*

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In this paper we will give an update of the Apollon 10 PW facility. The Apollon facility is currently under construction in France. Once the location of the building was decided mid 2010, it took roughly 4 years for refurbishing this former underground LINAC facility that is located close to the SOLEIL synchrotron at CEA Orme des Merisiers [1]. This facility has been inaugurated in September 2015 and itsinstallation is being carried out by the Laboratory for the Use of Intense Lasers (LULI), in partnership with CNRS and CEA. Apollon is one of the key scientific projects of Ecole Polytechnique [2].

Apollon laser system will be delivering 4 beams: one 10 PW beam (F1 beam 400 mm diameter), one 1 PW beam (F2 beam 140 mm diameter) and two additional probe beams (F3 and F4) at a repetition rate of 1 shot per minute.

The front-end was designed and built by Patrick George's team at the IOGS [4] and it has been already shown that the front-end will be delivering up to 30 mJ at 820 nm in less than 10 fs pulses at 10 Hz [4]. Once stretched to 1 ns duration in an Offner-type stretcher, the pulses are amplified in Ti-sapphire amplifiers pumped by frequency doubled solid-state lasers. While the low part (up to 3 J) are pumped by conventional green pump lasers, the high energy part is using the Atlas 100 Joule laser from Thales [5] for pumping a 30-J amplifier and the most powerful pump laser ever built by Continuum and National Energetics [6] for pumping a 100-J amplifier. The progress in output energy from the high energy amplifiers is only limited by the pump laser availability. We will give details about the results obtained together with an update of the facility equipment: the 10-PW compressor for F1 beamline, the 1-PW compressor for F2 beamline, the switchyard part for dispatching the four beamlines to the short focal length area (plasma physics experiments) and the long focal length area (electron acceleration).

Although the main 10 PW beam is designed with an expected 150 J/15 fs after compression, we have already achieved 30 J uncompressed than will be the first stage F2 beam once compressed.

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10238-25, Session 6

TW-class hollow-fiber compressor with tunable pulse duration

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CEP-stable few-cycle light pulses find numerous applications in attosecond science, most notably the production of isolated attosecond pulses for studying ultrafast electronic processes in matter [1]. Scaling up the pulse energy of few-cycle pulses could extend the scope of applications to even higher intensity processes, such as attosecond dynamics of relativistic plasma mirrors [2].

Hollow fiber compressors are widely used to produce few-cycle pulses with excellent spatiotemporal quality [3], where octave-spanning broadened spectra can be temporally compressed to sub-2-cycle duration [4,5]. Several tricks help increase the output energy: using circularly polarized light [6], applying a pressure gradient along the fiber [7] or even temporal multiplexing [8]. The highest pulse energy of 5 mJ at 5 fs pulse duration was achieved by using a hollow fiber in pressure gradient mode [9] but in this case no CEP stabilization was achieved, which is crucial for most applications of few-cycle pulses. Nevertheless, it did show that in order to scale up the peak power, the effective length and area mode of the fiber had to be increased proportionally, thereby requiring the use of longer waveguides with larger apertures. Thanks to an innovative design utilizing stretched flexible capillaries [10], we recently demonstrated the generation CEP-stable sub-4fs pulses with 3mJ energy using a 2m length 450mm bore hollow fiber in pressure gradient mode [11].

Here, we show that a stretched hollow-fiber compressor operated in pressure gradient mode can generate relativistic intensity pulses with continuously tunable waveform down to almost a single cycle (3.5fs at 750nm central wavelength). The pulses are characterized online using an integrated d-scan device directly under vacuum [12]. While the pulse shape is tuned, all other pulse characteristics, such as energy, pointing stability and focal distribution remain the same on target, making it possible to explore the dynamics of plasma mirrors using controllable relativistic-intensity light waveforms at 1kHz.

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10238-26, Session 6

Performance tests of the 5 TW, 1 kHz, passively CEP-stabilized ELI-ALPS SYLOS few-cycle laser system

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ELI-ALPS in Hungary, one of the three pillars of the Extreme Light

Infrastructure, aims at providing diverse light sources, including energetic attosecond pulses at the highest possible repetition rates. One of the main laser systems for driving plasma and gas-based HHG stages, is a state-of-the-art 1 kHz few-cycle laser called SYLOS. Targeted pulse parameters are an energy of 100 mJ and a duration shorter than two optical cycles (<6 fs), with outstanding energy, phase and pointing stability as well as high spatiotemporal quality.

The first phase of the laser system has already set a new standard in kHz laser system engineering and technology. The performance and reliability of the SYLOS laser have been consistently tested over the course of a six-month trial period. During this time the system was running at least 8 hours a day at full power for more than 5 months. The current output parameters are 5 TW peak power, 45 mJ pulse energy with 9 fs duration and 300 mrad CEP stability, while the spectrum spans over 300 nm around 840 nm central wavelength. The layout follows the general scheme NOPCPA architecture with a passively CEP-stabilized front-end. The pulses are negatively chirped for the amplification process and compressed by a combination of large aperture bulk glass blocks and positively chirped mirrors under vacuum conditions at the output.

During the trial period, the laser system demonstrated outstanding reliability. Daily startup and shutdown procedures take only a few minutes, and the command-control system enables pulse parameters to be modified instantly. Controlling the delays of individual NOPCPA stages makes it possible to tailor the output spectrum of the pulses and tune the central wavelength between 770 nm and 940 nm. We performed several experimental tests to find out the pulse characteristics. Pulse duration was verified with Wizzler, chirp-scan, autocorrelation methods and a stereo-ATI independently. All of them confirmed the sub-9 fs pulse duration. We recorded the long-term waveform and pointing stabilities of the beam in order to find out the effect of the temperature load on optical elements. Excluding a short initial warm up time, stable signals were observed in general. The in-loop and out-of-loop CEP stability was cross-checked between f-to-2f and stereo-ATI devices. Moreover, the inherent CEP stability of the system without feedback loop was also found to be surprisingly robust thanks to the passive CEP stabilization of the front-end. The polarization contrast was better than 1000:1. The temporal contrast was also measured independently with Sequoia and Tundra cross-correlators, and on the ns scale with a fast photodiode and GHz oscilloscope as well. Results showed that the pulse pedestal generally consists of parametric superfluorescence below the 1E-7 level and about 100 ps long, well in accordance with the pump duration. Delaying the pump pulse allows us to shift the seed pulse to the front and reach a pre-pulse pedestal below 1E-11 at 30 ps before the pulse peak. Detailed findings on all the examined pulse characteristics of the SYLOS laser will be reported in this presentation.

10238-27, Session 6

The optimization of a grating pulse stretcher for a 150 fs 10PW laser system

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A comparison of various pulse stretcher designs accommodating material dispersion for a 150 fs 10 PW Nd:glass laser system using low dispersion diffraction gratings is presented. Since the pulse amplification demands a high stretch ratio of the stretcher to suppress non-linear effects and a high temporal contrast of the pulse is required to avoid ionization of the experimental targets, the design of the stretcher is a very important tool for dispersion management. Here, we compare several designs using only one diffraction grating based on either a Perry-Banks or an Offner stretcher, mostly at the Littrow angle. The target spectral phase profile is achieved through the tuning of the grating position, the angle of incidence on the grating, the radii of curvature of curved mirrors and the line density of the grating.

10238-28, Session 7

Measurements of the optical anisotropy parameter in Yb:CaF2 crystals

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Crystals of CaF2 are used as the material for passive and active (with active ions Yb3+ [1]) optics. In case of active elements, heat generation could be significantly increased, thus the value of thermal effects also increases. One of the key thermally induced effect is the thermally induced depolarization that appears in optical element because of thermally induced birefringence and photoelastic effect. The main negative factor of thermally induced depolarization is power losses in the linear polarized incident component of field, phase and amplitude distortions of the field, after the optical element.

There are different methods of reducing of the value of thermally induced depolarization: cryogenic cooling of the optical element [2], using the optical materials with the best thermo optical properties [3], using the specific orientation of crystallographic axes of the sample, due to dependence of the depolarization on orientation of crystallographic axes [4]. The directions of the optimal orientation of crystallographic axes is determined by the optical anisotropy parameter and experimentally was shown, that in materials with negative optical anisotropy parameter there is the “zero depolarization” orientation in which depolarization vanishes [5].

In this paper we determined the optical anisotropy parameter of two samples of Yb:CaF2 crystal, with different Yb3+ concentration using two methods, described in [6], at the wavelength 1070 nm and compared with undoped CaF2. Also, the orientation of “zero depolarization” for studied crystals was calculated. According to experimental data, optical anisotropy parameter does not show the dependence on Yb3+ ions concentration in the (0 - 4) at.% range. Thus, the direction of “zero depolarization” orientation does not depend on Yb3+ concentration in investigated range. Obtained results are an addition to the studies of the temperature and spectral dependences of the optical anisotropy parameter of CaF2 crystal that were previously made [7, 8]. Values of the optical anisotropy parameter could be used in computational modelling of thermal effects in such materials.

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10238-29, Session 7

Effect of cryogenic temperature on spectroscopic and laser properties of Er, Yb-doped potassium-lanthanum phosphate glass

Richard ?vejkar, Jan ?ulc, Michal N?mec, Helena

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Glass matrix doped with rare-earth ions is promising laser active medium for high power laser systems. Due to amorphous structure of glasses the absorption and emission spectra lines are broader in comparison with crystaline materials thus pumping radiation can be absorbed efficiently, moreover much broader gain bandwidth is suitable for generation of ultra-short pulses. Another advantage of glass matrix is possibility of fabrication of large volume and preservation of sufficient optical quality. The lower thermal conductivity of glasses can be compensate by geometry of active medium, like fibres or discs. We present temperature dependence of spectroscopic and laser properties of newly developed Er, Yb - doped potassium-lanthanum phosphate glass, which is appropriate for generation of radiation at 1.53 μm. The sample of Er,Yb:KLaP glassy mixture (32.6K2O–6.3Yb2O3–7.4La2O3- 0.2Er2O3–53.5P2O5 (% mol)) was cut into disc shape with dimensions of 2.5 mm (thickness) and 5 mm (diameter) and its faces were polished plan-parallelly without being anti-reflection coated. During spectroscopy and laser experiments the Er,Yb:KLaP sample was attached to temperature controlled copper holder and placed into vacuum chamber. The temperature dependence of the transmission and emission spectra of Er,Yb:KLaP together with the fluorescence decay time were measured in temperature range from 80 to 400 K. With decreasing temperature the fluorescence lifetime of manifold 4I13/2 (upper laser level) became longer and intensity of up- conversion radiation was decreasing. The longitudinal excitation of Er,Yb:KLaP was carried out by a fibre- coupled laser diode (pulse duration 2 ms, repetition rate 10 Hz, pump wavelength 969 nm). Laser resonator was hemispherical, 145 mm in length with flat pumping mirror (HR @1.5 μm) and spherical output coupler (r = 150 mm, R = 98 % @1.5 – 1.6 μm). The Er,Yb:KLaP glass laser properties were investigated in the temperature range 80 - 300 K. The highest slope efficiency with respect to absorbed pumped power was 6.1 % at 80 K. The maximum output of peak amplitude power was 0.71 W at 80 K, i.e. 1.2 times higher than at 300 K. Tunability of laser at 80 K in range 1528-1552 nm was obtained using MgF2 birefringent filter. From our measurement can be concluded, that spectroscopic and laser properties of newly developed Er,Yb:KLaP glass are slightly temperature dependent. Therefore, its possible application for construction of temperature insensitive laser might be considered.

10238-30, Session 7

AlGaInN laser diode bars for high-power, optical integration and quantum technologies

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The AlGaInN material system allows for high power laser diodes to be fabricated over a very wide range of wavelengths from u.v., ~380nm, to the visible ~530nm, by tuning the indium content of the laser GaInN quantum well, giving rise to new and novel applications, including high power laser bars as pumps for diode pumped solid state lasers , individually addressable arrays for optical integration and for quantum technologies.

We report on our latest results of monolithic AlGaInN packaged in a common contact configuration and also laser arrays with each laser element individually addressable allowing complex free-space and/or fibre optic system integration with a very small form-factor.

10238-31, Session 7

Watt-level yellow emitting lasers by frequency doubling of high power diode lasers

Roland Bege, Daniel Jedrzejczyk, Julian Hofmann, Gunnar Blume, David Feise, Frank Bugge, Katrin Paschke, Günther Tränkle, Ferdinand-Braun-Institut (Germany)

Laser light sources emitting in the yellow spectral range at optical powers up to the watt-level are sought for many biomedical applications in particular for dermatology, ophthalmology and flow cytometry. Existing laser sources as dye lasers, copper-bromide lasers, etc. are inefficient, large-sized, highly toxic or maintenance-intensive. Therefore, highly brilliant diode lasers would be a possible approach to cope with these disadvantages. Suitable diode lasers emitting in the yellow spectral range have not been demonstrated, yet. Second harmonic generation (SHG) of diode laser radiation in the near infrared (NIR) wavelength range beyond 1100 nm would represent a significant improvement. Diode lasers meeting the requirements for conversion into the yellow spectral range up to the watt-level have just recently been introduced by our group at 1178 nm [1]. For simplicity reasons, a single-pass through the nonlinear crystal is favorable, since it allows cost-efficient micro-integration into hand-held modules with a footprint of a few cm. A periodically poled MgO-doped lithium niobate ridge waveguide crystal (MgO:ppLN) can be utilized for SHG, which is characterized by high conversion efficiencies. However, conversion with lithium niobate ridge waveguide crystals is usually restricted to a few hundred milliwatts of pump power due to absorption effects like green induced infrared absorption (GRIIRA) or photorefractive damage.

At the conference, we will demonstrate tapered diode lasers with monolithically integrated DBR-surface gratings (DBR-TPL) for emission at multiple wavelengths beyond 1100 nm (1122, 1156 and 1178 nm). The underlying diode laser structures are composed of highly compressively strained InGaAs quantum-wells and show a high reliability in stress-step tests due to strain compensation. As will be shown by the obtained results, the developed DBR-TPLs are well-suited for efficient SHG. The NIR-radiation is frequency doubled in MgO:ppLN ridge waveguide crystals in bench-top experiments. We will present results of nearly diffraction limited radiation with output powers up to 0.86 W [2] at 561, 578 and 589 nm. To the authors' best knowledge, these output powers are the highest values for SHG in ridge waveguide crystals reported so far. Although maximum SHG power densities in the ridge waveguide of up to 2.9 MW/cm are achieved, visible light induced infrared absorption appears not to be present. At the conference, we will show temperature and wavelength tuning measurements of the ridge waveguide crystals at various SHG output powers. The thermal effects on the ridge waveguide performance will be discussed in detail.

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10238-32, Session 7

Design of precise assembly equipment of large aperture optics

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High-energy solid-state laser is an important way to achieve laser fusion research. With the development of high power laser technology, the optics of modern high-energy solid-state laser has become larger and larger. Laser fusion facility includes thousands of various types of large

aperture optics. To make sure the device works safely and reliably, these large aperture optics should be installed with high precision and high efficiency. Currently the assembly of large aperture optics is by man's hand which is in low level of efficiency and labor-intensive. The large aperture optics are very fragile, heavy and expensive. We analyzed the actual operating conditions and technical principles of the assembly of large aperture optics . According to the characteristics of the precision assembly of large aperture optics. We designed three new kinds of grasping device which are used to complete the assembly of large aperture optics. The layout of pneumatic system is arranged. We simulated the impact of the grasping device on the PV value and the RMS value of the large aperture optics which indicated that the deformation of the large aperture optics were within a reasonable range. Using ANSYS, the structural strength of the grasping device's key parts were analyzed which indicated that the strength of the main support plate was enough to keep the device safely. An experiment was performed to illustrate the reliability and precision of the grasping device.

10238-33, Session 7

Power scaling of adaptive beam profiles in a dual-cavity configuration

Ji Won Kim, Seong Hyun Noh, Dong Joon Kim, Hanyang Univ. (Korea, Republic of)

Tailored laser beam profiles play the critical role in materials processing applications since the intensity distribution determines the resultant pattern of the targeted area, and the effects on the zone surrounding it. In addition, the optimized energy distribution allows improving the efficiency and speed of the processing dramatically. Therefore, there has been significant effort devoted to controlling the transverse beam profile of lasers, to optimize the conditions for various applications, particularly precision micro-machining. Recently, our group reported a new laser configuration, i.e. dual-cavity configuration, enabling adjustment of the spatial gain distribution in the laser medium simply by controlling the cavity losses in a primary and secondary cavity. As a result, we could achieve not only selective excitation of the fundamental (TEM00) or LG01 mode, but also generation of a tailored beam profile simply by controlling the relative contributions of both modes. However, its output power was limited less than 1 W due to thermal effects and energy migration.

Here, we report power scaling of a laser output with tailored beam profile from a donut to quasi-top-hat intensity distribution in master-oscillator power-amplifier. Exploiting a dual-cavity configuration with a single Nd:YAG crystal and a quarter-wave plate as an oscillator, a seed beam with the tailored beam profile could be generated by simultaneous excitation and control of the relative contributions of the fundamental (TEM00) and first order Laguerre-Gaussian (LG01) transverse modes. This seed beam was amplified in two-stage power amplifier yielding 15.1 W, 16.3 W and 17.6 W of the TEM00, LG01 and top-hat output respectively. We investigated the amplified beam profiles for various seed beams as a function of pump power and discuss the prospects for tunable laser beams profiles.

Conference 10239: Medical Applications of Laser-Generated Beams of Particles: Review of Progress and Strategies for the Future

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Part of Proceedings of SPIE Vol. 10239 Medical Applications of Laser-Generated Beams of Particles IV: Review of Progress and Strategies for the Future

10239-1, Session 1

Accelerator development for hadron therapy

Simon Jolly, Univ. College London (United Kingdom)

The technology used for modern particle therapy treatment has several decades of development behind it, with the accelerators that underpin them almost a century old. Since the opening of the first clinical proton therapy centre in 1986 at the Clatterbridge Cancer Centre in the UK, followed swiftly by the first clinical gantry-based system at Loma Linda in the US, clinical systems have consolidated around two complementary accelerator systems: cyclotrons and synchrotrons. The fundamental principles of operation of these two types of accelerator have remained largely unchanged, with the majority of commercial investment focussed on improvements in reliability and cost-effectiveness.

The mode of operation of these accelerators will be discussed, including the rationale for the dominant use of the oldest technology, the cyclotron, for modern clinical centres. An overview of the clinical requirements for hadron accelerators for radiotherapy will be given along with a comparison to conventional X-ray photon radiotherapy. Modern accelerator designs relevant to hadron therapy will be introduced with the motivation for these developments from both an accelerator and a clinical perspective. Finally, a comparison will be made with experimental accelerator technologies, including plasma wakefield acceleration, with a few cautionary tales thrown in for good measure

10239-2, Session 1

Proton therapy accelerator research in the UK

Hywel Owen, Univ. of Manchester (United Kingdom)

Proton tomography is seen as an important technique to improve the accuracy of proton therapy treatments, but is presently limited by the lack of a convenient source of the 350MeV protons needed for full adult imaging, even though 250MeV is now readily and economically achievable using conventional cyclotrons. NORMA is a 30-350MeV proton FFAG design to replace conventional cyclotrons that enables proton tomography and a higher rate of treatment, and details of this design will be presented. PROBE is a c.60MV/m proton linac design that may be used to upgrade existing c.250MeV cyclotrons, and details of its design and construction will be presented ahead of testing scheduled for 2017. Early designs for a novel superconducting gantry will be presented that may deliver 350MeV protons within the space currently needed for 250MeV protons. We are also constructing a 70-250MeV research beamline as part of the NHS proton treatment centre at Christie Hospital, which will enable a variety of technical, biological and clinical-related research once it becomes available in 2018. This work will be place in the context of the identified clinical and research needs in this field both in the UK and internationally.

10239-3, Session 1

Laser-driven particle acceleration for radiobiology and radiotherapy: where we are and where we are going

Antonio Giulietti, Consiglio Nazionale delle Ricerche (Italy)

The number of new cases of cancer in the world is expected to exceed 20 millions in 2020. Presently about 50% of cases are treated with radiation therapies, possibly in combination with surgery and/or chemotherapy. Among these treatments, more than 90% use RF-driven linear accelerators of electrons (RF-Linac). Other techniques include internal radiation (brachytherapy) and proton-ion beams (hadrontherapy). In most cases electrons delivered by a RF-linac are not used directly on the tumor but converted into hard X-rays. Radiation therapy techniques evolve and progress continuously and so do devices, sharing a global market of about $ 4 billions, growing at an annual rate exceeding 5%. Most of the progress involves precision in tumor targeting, multi-beam irradiation, reduction of damage on healthy tissues and critical organs, fractionation of dose delivering for a more effective cure. This fast evolving scenario is the moving benchmark for the progress of the laser-based accelerators in order to become appealing towards clinical uses.

As for electrons, both energy and delivered dose requested by radiotherapy are available with plasma accelerators driven by lasers in the power range of tens of TW but several issues have still to be faced before getting a prototype device for clinical tests. They include capability of varying electron energy, stability of the process, reliability for medical users.

On the other side hadrontherapy, presently applied to a small fraction of cases but within an exponential growth, is the primary option for the future of radiotherapy. With such a strong motivation, research on laser-based proton/ion acceleration has been considerably supported in the last decade, mostly in the direction of achieving the challenging performances requested by the clinical standards. A usable device for cancer therapy needs to produce 200-250 MeV protons and /or 400-450 MeV/u carbon ions. In order to really profit of the Bragg peak, no more than 1% energy bandwidth is requested. Further, to release a dose of therapeutic interest in a reasonable time, more than 1010 proton/s have to reach the tissue under treatment. None of these performances has been achieved so far with laser techniques.

In the meantime a rich crop of data have been obtained in radiobiological experiments performed with beams of particles produced with laser techniques. Though this research is still in progress, it may be the time of having a general overview on it. It is quite significant however that most of the experiments have been performed moving samples to laser labs, rather moving laser equipment to biolabs or clinical context. This give us the measure that laser community cannot so far provide practical devices usable from non-laser people.

10239-4, Session 1

The integrated laser-driven ion accelerator system and laser-driven ion beam radiotherapy

Paul R. Bolton, Ludwig-Maximilians-Univ. München (United States); Jörg Schreiber, Katia Parodi, Ludwig-Maximilians-Univ. München (Germany)

The high power laser driver affords detailed investigation of intense laser-plasma interactions for which energetic particle and photon yields can have a diagnostic role. Consequently there is promise for laser-driven energetic particle acceleration as a basis of candidate sources for innovative accelerator development. To date, much experimental enquiry at high intensity has addressed the candidate source issue in single shot (single laser pulse) mode. However, applications will typically require repetition rated delivery of particle beams that are stable, reproducible, controllable and suitably monitored. For laser-accelerated ions we then must consider the integrated laser-driven ion accelerator system or ILDIAS. Mindful of the potential for multiple applications, due emphasis on the integrated full system with an accelerator mindset is essential. A variety of applications can present a variety of ILDIAS requirements; one of the most stringent being laser-driven ion beam radiotherapy or LIBRT. The key challenge for LIBRT is then relevant ILDIAS research and development aimed at achieving adequate technical maturity (i.e. obtaining medical accelerator quality). For an effective long term strategy distinction between ILDIAS as the machine and LIBRT as the application is critical. In this presentation ILDIAS is defined and its progress toward LIBRT is assessed. Also points of guidance are given for realistic long term strategic planning. Given the recent impressive development of conventional accelerators by industry, cost/size issues and unique capabilities, as they pertain to LIBRT, can change rapidly. Therefore, comparative assessment must be ongoing with a commensurately developing and realistic vision for start-up implementation.

10239-5, Session 1

Recent progress in laser-driven proton acceleration from ultrathin foils

Paul McKenna, Univ of Strathclyde (United Kingdom)

In recent years a number of research groups have been working towards the challenging goal of developing laser-driven ion sources for potential application to hadron therapy. In addition to being potentially more compact, a laser-driven approach could also offer a number of advantageous features currently unavailable with conventional ion sources. The provision of different ion species is possible simply by changing the composition of the sample irradiated by the laser pulse, and thus multiple ion species could be simultaneously available for treatment, leading to improved dose localization. A laser-driven ion accelerator offers the possibility of controlling the ion beam spectrum directly at the source, which may enable the energy spectrum could be tailored to achieve a required dose deposition profile without the need for in-beam degrading techniques. In addition, the same laser driver can be used to produce other types of particles and radiation, such as energetic electrons and X-ray pulses, potentially enabling options for mixed field irradiation of tumors. Applications such as ion oncology have thus motivated a surge in research activity in the field of laser-driven ion acceleration, including the identification of several new acceleration mechanisms.

We report on results from our recent experimental campaigns, using the Astra-Gemini and Vulcan lasers at the Rutherford Appleton Laboratory in the UK, in which proton acceleration in ultrathin foils undergoing transparency is investigated. It is shown that in this regime the collective plasma dynamics can be manipulated by the transmitted portion of the intense laser pulse, enabling manipulation of the resulting beam of accelerated protons. In the case of ultrashort laser pulses, a relativistic plasma aperture is produced [1], enabling the spatial-intensity distribution of the proton beam to be changed by variation of the laser polarisation [2]. For longer pulses, plasma expansion results in relativistic self-focusing of the laser pulse, which forms a plasma jet, enhancing energy coupling to sheath-accelerated protons [3]. The maximum proton energy is shown to strongly depend on the rising edge intensity profile of the laser pulse on the picosecond time scale. We also report on coupled 3D particle-in-cell simulations, which show the potential to develop these approaches to optimise laser-driven proton acceleration.

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[2] B. Gonzalez-Izquierdo et al, Nature Communications 7, 12891 (2016)

[3] H. W. Powell et al, New Journal of Physics 17, 103033 (2015)

10239-6, Session 2

Applications of laser-wakefield-based x-ray sources: from bio-medical to global food security

Jean-Claude Kieffer, Sylvain Fourmaux, Institut National de la Recherche Scientifique (Canada); Emil Hallin, Global Institute for Food Security, Univ. of Saskatchewan (Canada)

Lasers found myriad applications in biomedical research [1]. We discussed previously [2] and very recently [3] the potential impact of ultrafast laser-based X-ray sources on medical imaging. In particular, laser Wakefield electron acceleration and related generation of high throughput hard X-rays might allow a paradigm shift in a wide range of applications [3]. Ultrafast laser wakefield accelerated electrons perform wiggler-like oscillations creating a very bright micrometer-sized highly directional emission x-ray source [4]. We demonstrated in 2011 at INRS [5], and simultaneously similar results were obtained at U. of Michigan [6], that one phase contrast hard x-ray image could be produced in one laser shot with a reasonable signal to noise ratio. This is opening a new route for fast 3D imaging of various objects [7].

In 2016, we upgraded our X-ray betatron beamline, which is now operated with 250 TW on target (6J, 25fs, 2.5Hz). We present the characterization of our LWFA betatron beam line, the X-ray source design parameters being 109 photons/0:1% bandwidth/sr/shot at 40 keV, a critical energy between 40 and 70 keV, effective X-ray source size of 1 μm, a divergence between 10 and 50 mrads (FWHM), an X-ray beam pointing stability and an X-ray energy stability in the 2% rms range. Such improvements in our betatron beam line parameters are not only the result of the laser beam energy and intensity increase on the target but are also related to the reduction of the laser beam imperfections as shown by our recent 3D PIC calculations [8] with the CALDER code [9]. Control of the phase and intensity distribution along the laser beam propagation axis inside the target has been introduced in the upgraded betatron beamline in order to maximize the generation of betatron radiation.

We illustrate the potential of this new beam line through two X-ray phase-contrast imaging applications. The first one is related to preclinical imaging and detection of thromboembolic events, micro-stroke and mini-stroke with specifically designed phantoms. The second one is on global food security. We describe our funded program in developing high throughput phase contrast screening system based on LWFA X-ray sources for plant imaging. This initiative, led by the U of Saskatchewan, aims to elucidate that part of the functional that maps specific environmental inputs onto specific plant phenotypes. Phase contrast betatron X-ray images of various plants are compared to thermal neutron images of same plants realized at the Canadian Nuclear Laboratory N5 Beam line.

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10239-7, Session 2

Nanomedical science and laser-driven particle acceleration: promising approaches in the prethermal regime

Yann A. Gauduel, Ecole Nationale Supérieure de Techniques Avancées (France)

An initial spatial distribution of energy deposition triggered by the interaction of ionizing radiations (UV and X rays, electron, proton and accelerated ions) with molecular targets or integrated biological systems is often decisive for the behaviour of radiation effects that take place on several orders of magnitude. The complex links that exist between the chemical physics of radiations and biomedical applications such as imaging and anticancer treatment (radio and chemo-radiotherapies) require the understanding of early events triggered by an initial energy deposition in confined sub-micrometric ionisation spaces (tracks).

This contribution deals with an interdisciplinary approach that concerns cutting-edge advances in real-time radiation events, considering the potentialities of innovating strategies based on ultrafast laser science, from femtosecond photon sources to advanced techniques of ultrafast TW laser-plasma accelerator. Recent advances of powerful TW laser sources (~1019 W cm-2) and laser-plasma interactions providing ultra-short relativistic particle beams in the energy domain 5-200 MeV open exciting opportunities for the development of high energy radiation femtochemistry (HERF). Early radiation damages being dependent on the survival probability of secondary electrons and radial distribution of short-lived radicals inside ionization clusters, a thorough knowledge of these processes involves the real-time probing of primary events in the prethermal regime, typically in the temporal range 10-14 - 10-11 s. In the framework of a closed synergy between low energy radiation femtochemistry (LERF) and the emerging domain of HERF, the lecture will focus on early phenomena that occur in the prethermal regime of low energy secondary electrons, considering very short-lived quantum effects in aqueous environments. The quantum character of a very-short lived electron state having a p-like configuration provides a unique and ubiquitous sub-nanometric probe to explore, at the local order, early couplings with a biomolecular sensor. After a low energy deposition due to biphotonic interactions of few eV, an effective reaction cross section of 200 A2 is defined at 500 fs. Experimental works are in progress for developing this concept with confined high energy ionisation density clusters (tracks), considering the specific properties of ultrashort laser driven electron bunches in the MeV domain. A high dose rate delivered by femtosecond electron beam (~1011-1013 Gy s-1) can be used to investigate early radiation processes in native ionisation tracks, down to 10-12 s and 10-9 m. We will explain how this breakthrough favours the innovating development of real-time nanodosimetry in biologically relevant environments and open new perspectives for spatio-temporal radiation biomedicine. New developments would permit to correlate early radiation events triggered by ultrashort radiation sources with a molecular approach of Relative Biological Effectiveness (RBE). The modulated response of biological endpoints, healthy cell survivals or carcinogenesis processes represents a real challenge to get the optimized control of ultra-high dose-rate effects at cell or tissue levels. These emerging research developments are crucial to understand simultaneously, at the sub-picosecond and nanometric scales, the early consequences of ultra-short-pulsed radiation on biomolecular environments or integrated biological entities, before the characterisation of clinical protocols devoted to pulsed radio-chemotherapy of cancers.

10239-8, Session 2

A comparative study of the biological effectiveness of MeV energy laser-driven electron bunches

Luca Labate, Consiglio Nazionale delle Ricerche (Italy); Maria Grazia Andreassi, Istituto di Fisiologia Clinica, Consiglio Nazionale delle Ricerche (Italy); Federica Baffigi, Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche (Italy); Andrea Borghini, Monica Cresci, Istituto di Fisiologia Clinica, Consiglio Nazionale delle Ricerche (Italy); Fabio Di Martino, Azienda Ospedaliero-Univ. Pisana (Italy); Lorenzo Fulgentini, Antonio Giulietti, Petra Koester, Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche (Italy); Debora Lamia, Istituto di Bioimmagini e Fisiologia Molecolare, Consiglio Nazionale delle Ricerche (Italy); Daniele Panetta, Silvia Pulignani, Istituto di Fisiologia Clinica, Consiglio Nazionale delle Ricerche (Italy); Giorgio Russo, Istituto di Bioimmagini e Fisiologia Molecolare, Consiglio Nazionale delle Ricerche (Italy); Claudio Traino, Azienda Ospedaliero-Univ. Pisana (Italy); Maria Tripodi, Cecilia Vecoli, Istituto di Fisiologia Clinica, Consiglio Nazionale delle Ricerche (Italy); Leonida A. Gizzi, Istituto Nazionale di Ottica, Consiglio Nazionale delle Ricerche (Italy)

An experimental study is reported aimed at comparing the biological effectiveness of laser-driven electron bunches to that of bunches produced by a conventional linac, in an energy range of interest for internal radiotherapy. Different biological endpoints, which include micronucleus frequency, telomere shortening and cell viability, were studied. The study of the acceleration regime, aimed at optimizing the electron-biological samples interaction geometry and maximizing the available dose in the selected energy range, will be first discussed, along with the dosimetric characterization of the electron source. Then, the results of selected biological assays carried out on samples irradiated either using laser-driven bunches or a IORT (Intra-Operatory Radiation Therapy) linac will be reported. Although no statistically significant differences were observed, some cell lines showed a trend toward decreased viability after exposure to the laser-driven electron pulses as compared to the irradiation with conventional linacs. Further investigations are in progress.

10239-9, Session 2

Homogenous depth dose profile experiments with laser-accelerated protons and pulsed high-field magnets for volumetric tumour irradiation studies

Florian-Emanuel Brack, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany) and TU Dresden (Germany); Karl Zeil, Florian Kroll, Stephan D. Kraft, Josefine Metzkes, Hans-Peter Schlenvoigt, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Lieselotte Obst, Martin Rehwald, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany) and TU Dresden (Germany); Elke Beyreuther, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Leonhard Karsch, Michael Schürer, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Jörg Pawelke, OncoRay - National Ctr. for Radiation Research in Oncology (Germany) and Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Thomas E. Cowan, Ulrich Schramm, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany) and TU Dresden (Germany)

Laser-driven ion acceleration has been considered a potential alternative for conventional accelerators like cyclotrons or synchrotrons and thus could provide a more compact and cost-efficient particle therapy solution in the future. The beam properties of laser accelerated beams strongly differ from the quasi-continuous beams generated by conventional accelerators. Laser accelerated beams exhibit fs to ps bunch length, carry up to 1013 particles with broad energy spectrum and are highly divergent. Thus, special measures are required to make use of the novel particle source, especially considering the goal of a future medical application.

Pulsed high-field magnets are a versatile and efficient way of shaping laser-accelerated beams both spatially and spectrally for application. Nevertheless, the bunches remain short and therefore intense, leading to high dose rates when stopped in matter. These dose rates make special demands for dosimetry and are a core aspect for radiobiological studies such as volumetric tumour irradiation studies. We present a beamline based on pulsed solenoid technology for effective collection and focusing of laser-accelerated protons. The solenoid magnet is powered by a capacitor-based pulse generator and can reach a maximum magnetic field of 20 T at currents exceeding 20 kA.

We performed experiments with the 600 TW beam of the Dresden laser acceleration source Draco to investigate homogenous depth dose distributions with laser-accelerated protons. Therefore, a setup of up to two solenoid magnets was used to efficiently capture and shape the beam. The spectra of the ion beam was then analysed with a Thomson parabola spectrometer, the dose distribution measurement was done via scintillator and radiochromic film.

The talk will focus on reliable generation of homogeneous dose distributions lateral and in depth. Practical issues, like magnet repetition rate and stability, mean dose rate and future radiobiological challenges will be discussed.

10239-10, Session 2

New approaches in clinical application of laser driven ionizing radiation (LDIR)

Katalin Hideghéty, Univ. of Szeged (Hungary); Robert Polanek, Tünde Tokés, Rita Emilia Szabó, Zoltán Szabó, ELI-ALPS Research Institute (Hungary)

The planned laser-driven ionizing beams (photon, very high energy electron, proton, carbon ion) at laser facilities have the unique property of ultra-high dose rate (>Gy/s-10), short pulses, and at ELI-ALPS high repetition rate, carry the potential to develop novel encouraging cyclotron, synchrotron, or reactor based radiotherapy methods toward compact hospital based clinical application.

Boron Neutron Capture Therapy (BNCT) is an advanced cell targeted binary treatment modality. The development of laser based thermal-epithermal neutron beams with as high as 1010 fluence rate could enhance the research activity in this promising field.

Proton Boron Fusion reaction (BPFR) is another binary approach, where the similar 11boron enriched compounds can be used. Due to alpha particle release during the BPFR the maximum point of the Bragg-peak is increased significantly. In addition, the prompt gamma ray emitted by the reaction can provide information about the therapy region. The more flexibility in particle and energy selection provided theoretically by LDPA could be highly beneficial in radiotherapy. All these approaches may increase the therapeutic index over the currently available advanced radiation oncology methods. The actual research of our group at ELI-ALPS in preparation for LDPA evaluating and validating special biological systems using zebrafish embryos, and rodent models for comparison of the effect of LDIR to that resulted in using conventional photon and electron beams will be presented.

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10239-21, Session 2

On the potential of laser driven PET isotope production at ELI-NP

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The huge progress made in the laser driven ion acceleration field had open the possibility of using ions generated by laser interactions with solid targets for the production of medical isotopes. Indeed, lasers could provide several key features with respect to the “traditional” method where the target activation is produced by a proton beam delivered by a cyclotron.

In our contribution, we review the main studies in the field and we present an analysis regarding the potential of the medical isotope production using lasers. We use laser simulations for deducing the beam parameters and a code implemented in Geant4 for computing the yields of the main production reactions, with an emphasis on the experimental conditions available at the ELI-NP facility, under construction now in Magurele, Romania. The obtained results are compatible with previous studies and will be verified by experiments foreseen at ELI-NP

10239-11, Session 3

Raman spectroscopy for oral cancer: a new diagnostic tool

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Background: In the clinical daily life, various lesions of the oral cavity have shown different aspects, generating an inconclusive or doubtful diagnosis. In general, oral injuries are diagnostic by histopathological analysis from biopsy, which is an invasive procedure and does not gives immediate results. In the other hand, Raman spectroscopy technique it is a real time and minimal invasive analytical tool, with notable diagnostic capability. The focus of this study is to show the evolution of the Raman technique in the oral pathology field in the last 10 years, starts from ex vivo samples results using FT-Raman spectroscopy, going through the oral cell lines characterization and finish in the very present study, which is the use of real time in vivo Raman spectroscopy.

Methods: In fact, the in vivo spectra from different sites of oral mucosa will be present. Different approaches will be show here utilizing Raman spectroscopy. A Kaiser Holospec system was used for in vivo experiments, each spectra collection was acquired with 10 seconds in the integration time, and some statistical multivariate methods, as principal component analysis, were used in order to discriminate the samples.

Results: After the statistical analysis, the groups from different oral mucosa sites were separated, also the comparing with the spectra between other pathologic groups. The spectral regions related to vibrational modes from proteins, lipids, carbohydrates and nucleic acids were relevant for the discrimination.

Conclusion: In conclusion, it was clear that the technique had an evolution during this period, obviously, a huge field exist for still increase and been in fact an important tool for clinicians during the clinical exam for oral cancer diagnostic in the early stages. Also, the technique could show which component is actually altered in the tissue.

10239-12, Session 3

Ion acceleration with kJ, multi-ps laser pulses on LFEX

Akifumi Yogo, Osaka Univ. (Japan)

Ion acceleration by high-intensity laser pulses has attracted a worldwide interest as a novel beam source.

Using kilojoule (kJ) class laser, we demonstrate for the first time that high-contrast pulses having a picosecond (ps) duration are advantageous for the ion acceleration.

As a result, we have achieved proton acceleration reaching 52 MeV at 1.2 X10^19 Wcm^-2 laser intensity.

The energy conversion efficiency from laser to protons above 6 MeV was evaluated to be 4% (40 J out of 1 kJ laser energy).

These results are quite encouraging for realizing ion beamlines.

The mechanism enabling the efficient proton acceleration will be discussed in the paper.

10239-13, Session 3

Guided post-acceleration of laser driven protons for medical applications

Satyabrata Kar, Queen’s Univ. Belfast (United Kingdom)

All-optical approaches to particle acceleration are currently attracting a significant research effort internationally. A recently developed concept of a versatile, miniature linear accelerating module to achieve simultaneous focusing, energy selection and post-acceleration of the proton beams will be discussed. In a proof-of-principle experiment on a 200 TW university-scale laser, guided post-acceleration of ~10^8 protons by ~5 MeV over less than a cm of propagation was demonstrated [1] – i.e. an accelerating gradient ~ 0.5 GeV/m, already beyond what can be sustained by conventional accelerator technologies. Using the technique at petawatt-class lasers, pencil beams of up to 50 MeV protons was obtained in our recent experiments. These results open up new opportunities for the development of extremely compact and cost-effective ion accelerators for both established and innovative applications.

10239-14, Session 3

Strongly focused very high energy electrons (VHEEs) as a new radiotherapy modality for delivering highly localised dose within a voxel volume

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Intensity-modulated radiotherapy (IMRT) using X-rays between 4 and 22 MeV is currently the most flexible method of delivering high radiation dose to a target volume while simultaneously protecting adjacent sensitive tissue. IMRT spreads the dose over a large volume of tissue while concentrating maximum dose within a tumour volume; however, its efficacy is still questioned by some [1] and it carries an increased risk of radiation induced malignancy [2],[3]. In contrast, modern radiotherapy modalities such as proton and ion beam therapies have been shown to be effective because of the combination of their high penetration, favourable dose distributions within tissue, and large radiobiological effect. However, their cost is currently considered prohibitive because of the large infrastructure required to transport beams to the patient [4].

An alternative modality that has been proposed is very high energy electrons (VHEEs) with energies above 60 MeV, which penetrate deeply into tissue where the dose can be absorbed within the tumour volume with a relatively small penumbra [5].

We show here how focussed VHEEs can deliver the dose to the tumour very effectively because focussing geometry provides superior tissue sparing and dose conformation to photons. The combination of very high energy electrons, low energy secondary electrons and bremsstrahlung radiation produced while VHEEs propagate through tissue are responsible for depositing high dose in a tiny voxel volume (6 mm focal spot at 15 cm water depth) with small penumbra (0.7 cm at 15 cm water depth) for a focussing geometry. This makes them suitable for delivering therapeutic radiation preferentially to the tumour volume. Furthermore, they have potential as an alternative modality to proton rastered conformal irradiation because they can be easily transported, shaped and focused. The laser wakefield accelerator (LWFA) is a new type of accelerator that provides a convenient and compact technology for producing high energy, ultra-short bunch electron beams over a very short length (2 mm). This significantly reduces the size and the costs of particle beam therapy compared with proton therapy, while providing some of its benefits.

We present a theoretical investigation of the physical properties and dosimetry of focused VHEEs carried out using Monte Carlo methods [6]. We present a comparative study that includes the percentage depth dose in a water phantom and the creation of voxels using both photon and VHEE beams for various geometries. We also discuss how the bunch duration for LWFA VHEEs can be used to control the dose rate with depth and compare this with VHEEs produced using a conventional linear accelerator. We present a focusing system designed for experiments at the SCAPA (The Scottish Centre for the Application of Plasma-based Accelerators) facility investigating focussed LWFA VHEE therapy.

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10239-15, Session PS

Autofluorescence diagnosis method in endoscopy for investigation mucosal structure in gastrointestinal tract

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Promising for the early diagnosis of malignant diseases of the respiratory organs and the gastrointestinal tract (GIT) is now considered a fluorescence method. This is due to its high sensitivity, making it possible to determine negligible concentrations of biologically active compounds. Feature fluorescence nature associated with the dependence of its parameters from the microenvironment of luminescence centers, the steric and electronic structure of molecules, the degree of aggregation makes it possible to study living tissues and organs, as for some of the fluorescence characteristics it is possible to monitor the changes in the functional state of these objects in particular to diagnose pathological conditions of the organism.

The aim is to develop a fluorescent light source (illuminator FLU) for videoendoscopy complex and determining on the basis of scientific research and prototyping capability for creating fluorescence video endoscope. The solution of the problem based on the method of the study of biological objects in vivo. From the viewpoint of hardware part is necessary to familiarize with existing diagnostic methods, evaluate the possibility of future interaction of the device with a real person from a security perspective. To develop the algorithm works and to purchase basic elements. To develop the scheme and to ensure its stable and reliable operation. It is necessary to take into account the requirements of state standards (GOST, ISO) laser safety, laser emission, medical requirements in the application of this technique. The results should be tested on a real instrument. Developed fluorescence illuminator allows to diagnose the patient's gastrointestinal tract without prior proper training to the patient survey and without additional costs for chemical dyes and other medical supplies. Scientific novelty lies in the safe diagnosis of the presence of cancer and other diseases in the digestive tract in situ (in place). Fundamentally the new scheme and the lighting device unit. The use of fluorescence phenomena in endoscopy. During the implementation of the R&D the following tasks and questions have been performed and resolved:

- confirmed the possibility of creating a fluorescent light for video endoscopy;
- developed all components and block diagrams;
- purchased materials and supplies needed to complete the work of the lighting unit;
- purchased performed calculations of optical systems, laser systems, the design parameters.

Developed videoendoscopy complex has no analogues in the domestic market. The only competitor in the world is the Japanese manufacturer OLYMPUS. But their unit has several disadvantages:

- heavier almost three times;
- large dimensions;
- less lifetime.

For today on prototype illuminator FLU conduct mechanical tests. In

the near future it is planned to conduct medical tests. There are many features and means of development and modernization of the developed lighting unit. After technical and medical tests we can accurately to understand which way we develop and aspire to become leaders in the production of auto-fluorescence video endoscopy in the world market.

10239-16, Session PS

The study of efficiency laser parameter for nondamaged biostimulation

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This study was designed to find an effective way of bio-stimulation through the laser irradiation on the human skin without tissue damage. For this purpose, the effect of laser irradiation on collagen membrane, one of major protein substances of human body, under varying conditions was observed. The result of the experiment confirmed the role of laser parameter in controlling stimulus intensities under proper adjustment. Also, the result confirmed that high stimulus intensities can cause tissue damage. Laser has its strong advantage in that it can stimulate tissue with varying intensities, without direct contact. The results of this study are applicable to the field of bio-stimulation for successful pain treatment.

10239-17, Session PS

Simulation of the skin temperature changes induced by 809 nm laser irradiation

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This study was designed to analysis the internal-skin temperature distribution under laser absorption of 809 nm wavelength. For the experiment, skin tissue was modelled into two layers, epidermis and dermis, and internal-skin temperature distribution was analysis according to the changes of laser parameter. The result of the experiment confirmed that the intensified laser peak power caused the increasing amount of thermal energy transferred to internal-skin, which led to the increasing amount of stress level on internal-skin. Further study on this issue will be about exploring the correlation between internal-skin temperature change and thermos-elastic effect. The results of this study are applicable to the field of bio-stimulation; such as recovery promotion of yeast-glucan, inflammation and general pain.

10239-18, Session PS

Modeling of the laser device for the stress therapy

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Recently there is a great interest to the drug-free methods of treatment of various diseases. For example, color therapy is used for the stress treatment. The main destination of the method is the health care and well-being.

Visual content in the given case is formed when laser radiation is passing through the optical mediums and elements. The therapy effect is achieved owing to the color varying and complicated structure of the picture which is produced by the refraction, dispersion effects, diffraction and interference.

The installation was created based on the project “Lux Aeterna Theatre”. The installation includes the light mountable construction – the semisphere dome with reflective coating, in the middle is the chair for the user.

The picture projection is performed according to the full-dome principle projection. It means that the image is projected to the semi-sphere dome, and due to this we have additional effect of immersion to the visual medium.

As the laser source we use three laser sources of 445 nm, 520 nm and 640 nm with the optical power of 1 W. Three lasers are brought together using the dichroic mirrors. The beam is guided to the optical element which is responsible for the final image of the dome surface. The dynamic image can be achieved by the rotating of the optical element when the laser beam is static or by scanning the surface of the element.

The optical elements used were round cylinder with hatching on the surface, plane plate with relief surface, tube of complicated form with the complex surface made by glassblower, reflective element made from polymer which changes the form under the thermal effect of the laser, or the silicon oil on the reflective surface. In the last two cases we have dynamic picture depending on the thermal properties of the polymer or the viscosity of the liquid, respectively.

Previous research has shown that the complexity of the image connected to the therapy effect. The image was chosen experimentally in practice. The evaluation was performed using the fractal dimension calculation for the produced image.

The pilot study was performed using the group of 30 persons which evaluated the stress before and after the therapy session using Luescher Color Test and the Zung self-rating depression scale. This study has proved the positive therapy effect of decreasing the anxiety.

In this work we model the optical image on the surface formed by the laser sources together with the optical element. Modeling is performed in two stages. On the first stage we perform the simple modeling taking into account simple geometrical effects. On the second stage we consider the wave properties. The performed modeling can allow predicting image effects depending on the form, sizes and divergence of the laser beams and quality of bringing the lasers together. Additionally, it can help to optimally choose the laser parameters for such installations and evaluate necessary accuracy of positioning the laser beams and also their necessary transformations.

10239-19, Session PS

The meat product quality control by a polarimetric method

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Traditional polarimetry is well suited for applying in optically pure environments and to research the surface, however, the multiple scattering in optically turbid media, causing extensive depolarization than confuses existing methods.The result of the operation, it was found that a high concentration of scattering particles, their size heterogeneity and shape make the task of constructing the optical model adequate biological tissue rather difficult, although a bunch of potentially interesting properties of the tissue could be examined using polarized light. As the sample treated biological tissue slice of the meat product.

Meat and meat products are among of the most valuable products, which have a significant share in the nutrition of the population. The ingredients which included in a meat are raw material for building tissue, necessary biosynthesis systems that regulate the body’s vital functions. The normal development of the body, human health and the ability to work depend on the food quality, so it requires strict control of the freshness of the products, and in the first place - the meat. In this regard, currently it’s important to develop a device for determining the freshness of raw meat and for determining its putrefaction on the early stage of deterioration.

There is a generalized method in a science for polarimetric analysis in turbid media, which is based on the decomposition of the Mueller matrix.

Using the method of Mueller matrix decomposition, the intensity of the light beam is represented as a four-element vector Stokes. In a such turbid media as tissue is, usually observed following polarimetric effects - depolarization, linear birefringence and optical activity. They often exist simultaneously, and each of them extracted separately from the Mueller matrix, is promising as a useful biological characteristic. And this is a research which directed on the experimental study of biological tissues.

After a review of existing schemes and the assessment of the problem was developed an experimental scheme, taking into account the subtleties of working with such a complex model as biological tissue.The main feature of the scheme of the device is its vertical position, is used to eliminate the biological tissue sample deformation. The experimental procedure involves coherent radiation illuminated the sample with a predetermined polarization state. After passing through the sample and block that makes a phase shift, the radiation forms on the photosensitive area of the receiver scattering spot. With the help of special software to measure the illumination on matrix receiver of optical radiation with all the necessary relative positions of the polarizer, analyzer and a phase plate. Further there is a calculation of the four parameters of the Stokes vector for the forward scattered radiation, and calculated the following parameters: an azimuth, an ellipticity, a degree of polarization.

Preliminary measurements were carried out on a sample of pork. The cut product was monitored for about a day, during which the organoleptically obvious changes were noted state of freshness of the sample. Processing of the experimental data showed a steady decline in the degree of polarization in the process damage the meat product.

Thus, the experimental installation scheme was developed for the installation of the changes in the polarized laser parameters transmitted through the biological media with the passage of time, and processing is realized the possibility of results. The experiments demonstrated the ability to work with a model of meat in the food industry, have shown the prospects of development of this theme including the way of more frequent measurement cycles for the same sample, with different sources of light and different patterns of meat breeds.

10239-20, Session PS

Study of biological effects of femtosecond IR laser beam filamentation for cancer therapy

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Some new studies reveals some physicochemical processes induced by femtosecond IR laser filamentation in transparent liquid media which can be interesting from biomedical point of view. A femtosecond laser filament in aqueous media can generate water radiolysis species, highly reactive free radicals, or reactive oxygen species in same way as the ionizing radiation, which can react with the cellular DNA, thereby producing mutation and cell death. Furthermore the femtosecond IR laser pulses in semi transparent or optically diffuse media, such as the tissue, has an opto-mechanical effects detectable microscopically. This opto-mechanical effect can be a sign of filamentation formation and propagation in such media, but the formation mechanism and characteristics are unclarified. One extreme statements of ongoing studies in this field is that this effects can be utilized for cancer therapy as an ideal radiotherapy agent with a well-controlled macroscopic dose distribution and very high dose rates. But this statement raise a series of questions which in present are unanswered and arouse doubts about such applications.

Before any clinical applications, it is mandatory to well understand the physics of laser filaments in water and transparent and semitransparent biological mediums, and the chemical and biological processes induced by the laser filamentation. The aim of this project is to determine the biomedical aspects of femtosecond IR laser filamentation, to demonstrate the filament formation in optical opaque mediums and to demonstrate some potential applications of it. In our preliminary experiments we used the TeWaTi laser system, Department of Optics and Quantum Electronics, University of Szeged, with 800 nm central wavelength and ~50 nm FWHM. The system generate pulses with 200 Hz repetition rate and less then 25 fs pulse duration. The used energy of beam was between 25μJ and 1mJ/pulse. In actual stage we have demonstrated some chemical effects of filamentation in transparent and semitransparent liquid media which can induce biological effects. Based on this effects we try to establish a dosimetric formalism to characterize the absorbed energy versus biological effects relationship. Furthermore we can demonstrate a filament like mechanical effects in mouse brain tissue and tissue-like gel materials (artificial tissue) when we used a fetmosecond laser pulse focused under tissue surface, such as was reported in few other publications. The magnitude and form of this filament like damages seems to be energy dependent. Furthermore the form of this damages is dependent of depth of focus point, but the exact behavior and properties needs additional studies.

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10240-1, Session 1

Generation of monoenergetic ion beams via ionization dynamics *(Invited Paper)*

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The research on ion acceleration driven by high intensity laser pulse has attracted significant interests in recent decades due to the developments of laser technology. The intensive study of energetic ion bunches is particularly stimulated by wide applications in nuclear fusion, medical treatment, warm dense matter production and high energy density physics. However, to implement such compact accelerators, challenges are still existing in terms of beam quality and stability, especially in applications that require higher energy and narrow bandwidth spectra ion beams.

We report on the acceleration of quasi-mono-energetic ion beams via ionization dynamics in the interaction of an intense laser pulse with a solid target. Using ionization dynamics model in 2D particle-in-cell (PIC) simulations, we found that high charge state contamination ions can only be ionized in the central spot area where the intensity of sheath field surpasses their ionization threshold. These ions automatically form a microstructure target with a width of few micron scale, which is conducive to generate mono-energetic beams. In the experiment of ultraintense (> 10^21 W/cm^2) laser pulses irradiating ultrathin targets each attracted with a contamination layer of nm-thickness, high quality > 100 MeV mono-energetic ion bunches are generated. The peak energy of the self-generated micro-structured target ions with respect to different contamination layer thickness is also examined

This is relatively newfound respect, which is confirmed by the consistence between experiment data and the simulation results.

10240-2, Session 1

Laser proton acceleration from liquid crystal films of different thicknesses with ultrahigh laser contrast

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The performance of laser based ion acceleration strongly depends on the laser temporal contrast and its effect on the target plasma scale length. Plasma mirror setups have proven to be a valuable tool to improve the temporal contrast by several orders of magnitude, reducing the intensity of pre-pulses that emanate from the laser chain and steepening the rising edge of the main laser pulse. We present recent results obtained at the Titanium Sapphire laser system Draco, delivering 30 fs long laser pulses at an intensity exceeding 10^20W/cm^2. Our recently commissioned single plasma mirror improves the contrast by four orders of magnitude while reflecting 80% of the initial pulse energy. Its influence on the laser proton acceleration process was studied in a campaign in collaboration with the High Energy Density Physics Group of Ohio State University using their tunable liquid crystal film target source. This device allows an on-demand variation of the target thickness from tens of micrometers down to 10 nm while keeping the target composition constant. The target was positioned under 45 degrees with respect to the incoming laser beam while accelerated protons and ions were monitored in both laser- and target normal direction by means of Thomson Parabolas and Radiochromic Film stacks. Hence, being sensitive to the identification of acceleration regimes beyond the well-known Target Normal Sheath Acceleration, preliminary results display a significant increase in proton cut-off energy when reaching thin targets. Up to 25 MeV could be observed for an optimum target thickness of 10 nm as compared to the few- micron scale reference for this target configuration of roughly 12 MeV.

10240-3, Session 1

High-contrast laser-proton acceleration from a condensed hydrogen jet

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Demanding applications like radiation therapy of cancer have pushed the development of laser plasma proton accelerators and defined levels of control and necessary proton beam stability in laser plasma experiments. The presentation will give an overview of the recent experiments for laser driven proton acceleration with high contrast at the high power laser Draco at HZDR. Draco delivers pulses of 30 fs and 5 J at 800 nm, focused to a 3μm spot by a F/2.5 off-axis parabolic mirror. We present results of an experimental campaign employing a pure condensed hydrogen jet as a renewable target. The jet's nominal electron density is approximately 30 times the critical density and its diameter can be varied to be 2μm, 5μm or 10μm and thus allowing to study the regime of relativistic transparency. Different ion diagnostics reveal mono-species proton acceleration in the laser incidence plane around the wire-like target. Radiochromic film stacks in forward direction display signatures of filament-like structures, stemming from a Weibel-like instability generated at the rear side of the target in the underdense plasma region. Additionally, the expanding jet could be monitored on-shot with a temporally synchronized probe beam perpendicular to the pump laser axis. Recorded probe images taken on a 10 ps timescale indicating instabilities from pinching effects in the plasma density along the jet axis. A possible driver for those instabilities is a surface current which has been studied with 2D-PIC Simulations. In addition the plasma density modulation shows an asymmetric behavior produced by the laser-plasma interaction.

10240-4, Session 1

Ion wave breaking acceleration

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We will introduce an alternative approach for laser driven self-injected

high quality ion beam acceleration. We call it ion wave breaking acceleration (IWBA). It operates in relativistic self-transparent plasma for laser intensities in the range of 10^20?10^23 W/cm^2.

When propagating a laser pulse in a transparent plasma, a co-moving cold ion wave can be produced. When driven strongly, the ion wave can break and a fraction of ions can be self-injected into the laser driven wake. The wake is square-wave like and sensitive to the injected ions. After an ultra-fast injection, the wake is weaken, then there is no further injection. This leads to a superior ion pulse with peaked energy spectra; in particular in realistic three-dimensional (3D) geometry, the injection occurs localized close to the laser axis producing highly directed bunches.

This work was done with the help of particle-in-cell (PIC) simulations by using the code PSC (H. Ruhl, Classical particle simulations, in Introduction to Computational Methods in Many Body Physics, edited by M. Bonitz, and D. Semkat (Rinton, Paramus, New Jersey, 2006)). In 1D and 3D PIC simulations, a circularly polarized ultra-intense laser pulse with a steep front edge rising over one laser period is irradiated on an uniformly distributed near critical density plasma. By scanning different laser intensities and plasma densities, it is shown that there are three distinct regimes: linear ion wave (LIW), IWBA, and the so-called hole-boring. In the regimes of LIW and IWBA, the plasma is relativistically self-transparent. Analytical results of the laser propagating velocity and the final ion energy in IWBA regime, which both uniquely depend on the ratio of the laser electric field amplitude to the initial plasma density, are obtained according to a simple model of the macroscopic behaviour of electrons, combining with the pressure balance between the laser radiation and the laser driven self-generated electrostatic field. The self-steepening of an initially gaussian laser pulse and applying of it for IWBA have been investigated with the help of 2D PIC simulations. IWBA in plasma with multi-component of ions and non-uniform density profile have also been investigated.

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10240-5, Session 1

Energetic ion bunches produced in under-dense plasmas by an intense laser pulse

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The mechanisms of the laser acceleration of ions in under-dense or near-critical plasmas (gas, foams) are at their early stage of development [1, 2, 3]. They offer a better laser/electron coupling than in solid targets resulting in a more efficient ion acceleration. They also enable a high repetition rate operation and reduce the formation of debris which could damage the interaction chamber.

Our work deals with this interaction regime and focuses on understanding how electrons and ions absorb energy from the laser pulse in low density plasmas. This interaction regime involves various non linear processes that strongly modify the particle distribution functions and induce strong non-local effects. The numerical simulations were performed with the Particle-In-Cell (PIC) code OCEAN [4].

By one dimensional PIC simulations, we have shown [5] that the interaction of a 1 ps long relativistic laser pulse with a under-critical homogeneous (0.5 n_c) plasma leads to a very high plasma absorption reaching 68 % of the laser pulse energy. By a very detailed analysis of the electrostatic and electromagnetic wave spectra in the plasma and a confrontation with the theory [6], we have demonstrated that this energy transfer originates from the process of stimulated Raman scattering in the relativistic regime. Due to the increase of the effective mass of the electrons oscillating in the relativistic laser wave, this instability occurs in plasmas with a density significantly larger than the quarter of critical density and permits a homogeneous electron heating all along the plasma followed by an efficient ion acceleration at the plasma edges. We also have observed the formation of cavities [7], which lead to the formation of quasi-monoenergetic bunches of ions inside the plasma.

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10240-6, Session 2

Intense Ion, neutron and hard X-ray beams from relativistic laser-matter interaction

Markus Roth, Annika Kleinschmidt, Oliver Deppert, Gabriel N. Schaumann, Alexandra Tebartz, Victor A. Schanz, Technische Univ. Darmstadt (Germany); Juan Carlos Fernández, Sven Vogel, Andrea Favalli, Donald C. Gautier, Randall P. Johnson, Michael Mocko, Glen Anthony Wurden, Los Alamos National Lab. (United States); Katerina Falk, ELI Beamlines (Czech Republic); Ishay Pomerantz, Tel Aviv Univ. (Israel)

The quest for laser-based high-energy ions and secondary radiation for applications like material research or even cancer treatment has been going on for some years. Recently, using high contrast short pulse lasers like the TRIDENT in the US or PHELIX laser in Germany laser and the concept of relativistic transparency, a breakthrough has been achieved with ion energies exceeding 100 MeV and the production of intense neutron pulses [1], only about three orders of magnitude weaker than the LANSCE neutron pulses.

Based on the new mechanism's advantages, a laser-driven deuteron beam is used to achieve a new record in laser-neutron production in intensity, energy and directionality. Thus, we demonstrated the use of short pulse lasers to use the resulting hard X-Rays and neutrons of different energies to radiograph an unknown object and to determine its material composition [2]. Neutron generation, scale exponentially with energy of the deuterium beam, which scales with the energy of the accelerating laser and result in a collimated beam, allowing e.g. a much higher fraction of produced neutrons to be captured by the moderator and delivered to the application. With available laser power increasing and the prospected increase in repetition rate and therefore average power, pulsed neutron sources achieving the neutron output of LANSCE or even SNS are conceivable. Since comparably little shielding is required, targets for laser neutron sources can be very compact, allowing moderator to sample/detector distances of a meter or even less, further increasing the flux on the sample. Investment and operational cost as well as real estate foot-print for the necessary laser systems are all a small fraction of those for the particle accelerators or reactors required for present neutron sources. We quantitatively compare the initial experiments in laser neutron generation with existing conventional sources. An overview and outlook on the developments in laser technology will be presented and the potential for neutron production will be outlined.

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10240-7, Session 2

Laser-based fast-neutron spectroscopy

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Tebartz, Technische Univ. Darmstadt (Germany); Juan Carlos Fernández, Donald C. Gautier, Randall P. Johnson, Tsutomu Shimada, Glen Anthony Wurden, Los Alamos National Lab. (United States); Markus Roth, Technische Univ. Darmstadt (Germany)

Great progress has been made in recent years in realizing compact, laser-based neutron generators. These devices, however, are inapplicable for conducting energy-resolved fast-neutron radiography because of the electromagnetic noise produced by the interaction of a strong laser field with matter. To overcome this limitation, we developed a novel neutron time-of-flight detector, largely immune to electromagnetic noise. The detector is based on plastic scintillator, only a few mm in size, which is coupled to a silicon photo-multiplier by a long optical fiber.

I will present results we obtained at the Trident Laser Facility at Los Alamos National Laboratory during the summer of 2016. Using this detector, we recorded high resolution, low-background fast neutron spectra generated by the interaction of laser accelerated deuterons with Beryllium. The quality of these spectra was sufficient to resolve the unique neutron absorption spectra of different elements and thus it is the first demonstration of laser-based fast neutron spectroscopy.

I will discuss how this achievement paves the way to realizing compact neutron radiography systems for research, security, and commercial applications.

10240-8, Session 2

Laser-driven proton acceleration with nanostructured targets

Simon Vallières, Institut National de la Recherche Scientifique (Canada); Antonia Morabito, ELI-ALPS Research Institute (Hungary); Simona Veltri, Massimiliano Scisciò, Marianna Barberio, Patrizio Antici, Institut National de la Recherche Scientifique (Canada)

Laser-driven particle acceleration has become a growing field of research, in particular for it's numerous interesting applications. One of the most common proton acceleration mechanism that is obtained on typical commercially available multi-hundred TW laser systems is based on the irradiation by the intense laser of thin solid metal foils, generating the proton acceleration on its rear target surface. Improving the acceleration mechanism, i.e. enhancing parameters such as maximum proton energy, laminarity, efficiency, monocromaticy, and number of accelerated particles, is heavily depending on the laser-to-target absorption, where evidently cheap and easy to implement targets are best candidates.

In this work, we present nanostructured layer-targets that are able to increase the absorption of light compared to what can be achieved with a classical solid (non-nanostructured) target and are realized with a method that is much simpler and cheaper than conventional lithographic processes. This allows for an enhanced particle yield in the proton production. Experimental results obtained on the TITAN laser located at LLNL are presented and compared to Particle-In-Cell simulations.

10240-9, Session 2

Isochoric heating of solid gold targets with the PW-laser-driven ion beams

Sven Steinke, Qing Ji, Stepan S. Bulanov, Lawrence Berkeley National Lab. (United States); John Barnard, Lawrence Livermore National Lab. (United States); Henri Vincenti, Thomas Schenkel, Eric H. Esarey, Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

We present first results on ion acceleration with the BELLA PW laser as well as end-to-end simulation for isochoric heating of solid gold targets using PW-laser generated ion beams: (i) 2D Particle-In-Cell (PIC) simulations are applied to study the ion source characteristics of the PW laser-target interaction at the long focal length (f/65) beamline at laser intensities of ~?5?10?^19 Wcm-2 at spot size of ?0=53 ?m on a CH target. (ii) In order to transport the ion beams to an EMP-free environment, an active plasma lens will be used. This was modeled [1] by calculating the Twiss parameters of the ion beam from the appropriate transport matrixes taking the source parameters obtained from the PIC simulation. (iii) Hydrodynamic simulations indicate that these ion beams can isochorically heat a 1 mm3 gold target to the Warm Dense Matter state.

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10240-10, Session 2

Controlling laser-ion acceleration through pulse chirping

Felix Mackenroth, Max-Planck-Institut für Physik komplexer Systeme (Germany); Arkady A. Gonoskov, Mattias Marklund, Chalmers Univ. of Technology (Sweden)

We present the latest results of the recently proposed laser-ion acceleration mechanism “Chirped-Standing-Wave Acceleration”. Here the electrons of a thin plasma layer are locked to the moving nodes of a standing wave formed by reflecting a chirped laser pulse from a mirror behind the thin layer. The layer's residual ions are then accelerated by the longitudinal charge separation field resulting from the electrons' displacement. The standing wave stabilizes the plasma layer, suppressing the formation of plasma instabilities. And the experimentally tunable laser chirp provides a versatile tool for manipulating the resulting ion beam's maximum particle energy, particle number and spectral distribution. Through this scheme, proton beams, with energy spectra peaked around 100 MeV, were shown to be feasible for pulse energies at the level of 10 J.

10240-11, Session 3

Collective electron and ion dynamics in ultrathin foils undergoing relativistic self-induced transparency

Paul McKenna, Univ. of Strathclyde (United Kingdom)

Understanding the collective response of charged particles to intense laser radiation is both of fundamental interest and important to the development of laser-driven accelerators. The case of ultra-thin foil targets which become relativistically transparent to the laser pulse during the interaction is of particular interest due to their importance in laser-driven ion acceleration. The onset of transparency makes radiation pressure acceleration ineffective, but can also enhance the energy of sheath-accelerated ions.

We report on experiment and 3D PIC simulation results on the collective response of plasma electrons and ions to an intense laser pulse propagating through an expanding ultrathin foil which becomes relativistically transparent. These results are the subject of recent papers in Nature Physics [1] and Nature Communications [2]. It is shown that a beam of energetic electrons is produced with spatial structure which can be controlled by variation of the laser pulse parameters. A ‘relativistic plasma aperture’ with a diameter of a few times the laser wavelength is produced at the peak of the focused laser pulse. Diffraction of the laser light propagating through this aperture produces a structured near-field diffraction pattern, to which the electrons collectively respond. It is demonstrated that static and rotating electron beam profiles can be induced by variation of the degree of ellipticity of the laser polarization [1]. The resulting modulation of the charge-separation-induced electrostatic field means that the ion motion can also be manipulated [2]. These concepts have been verified through experimental investigations and 3D particle-in-cell simulations and provide a new avenue of optical control of laser-accelerated electron and ion beams.

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10240-12, Session 3

Characterisation of collimated, high-density jets of multi-MeV electrons from near critical density targets

Nicholas M. H. Butler, Ross J. Gray, Martin King, Rachel J. Dance, Adam Higginson, Samuel Williamson, Univ. of Strathclyde (United Kingdom); Chris Armstrong, Univ. of Strathclyde (United Kingdom) and STFC Rutherford Appleton Lab. (United Kingdom); David Neely, STFC Rutherford Appleton Lab. (United Kingdom); Paul McKenna, Univ. of Strathclyde (United Kingdom)

The interaction of a sufficiently intense laser pulse with an ultra-thin (< 40nm) solid density target leads to a rapid heating of the constituent plasma electrons to relativistic velocities and a subsequent expansion of the target, resulting in the onset of relativistically induced transparency. Under these conditions, a high energy, low-divergence component of the proton beam has been experimentally observed [1,2]. Subsequent numerical investigations examining this phenomenon suggested that ion acceleration is strongly influenced by the intra-pulse transition from an opaque to a relativistically transparent plasma. Characteristic features of three distinct ion acceleration mechanisms were identified: sheath acceleration, radiation pressure acceleration, and transparency-enhanced acceleration, with the formation of a magnetised plasma jet mediating the latter process [3,4]. Electrons trapped within this jet experience a direct acceleration to supra-thermal energies by the portion of the laser pulse transmitted through the target. The resulting streaming of electrons into the layers of expanded sheath-accelerated ions enhances their energy in the vicinity of the jet, leading to a collimated, high energy component of the proton spatial distribution.

We report on new experimental measurements of the properties of these jets, including measurements of a self-generated, azimuthal magnetic field that supports the jet as it propagates into the expanded plasma layer at the rear of the target. Numerical simulations of the generation and propagation of the jet are also presented.

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10240-13, Session 3

Relativistic transmittance of a circularly polarized laser pulse in over-dense plasmas during hole-boring process

Teyoun Kang, Young-Kuk Kim, Min Sup Hur, Ulsan National Institute of Science and Technology (Korea, Republic of)

Since it became feasible to experimentally accelerate ions with ultra-intense laser pulses, relativistic transmittance (RT) also has become an issue that must be understood precisely. Various acceleration models have been investigated: TNSA, RPA, BOA, magnetic vortex, etc. Each model requires different RT conditions. For example, in radiation-pressure-acceleration (RPA) system, zero transmittance leads to the highest momentum transfer from the pulse to the ions. Meanwhile, in collisionless-electrostatic-shock (CES) system, it was recently found that a circularly polarized (CP) laser pulse with high transmittance could generate the shock efficiently, owing to the effective heating of upstream electrons by transmitted portion of the driving pulse. Because the RT determines the momentum transfer from the driving pulse to the particles, and also the heating, it is important to understand RT in realistic conditions. In previous theories, they required electron density distribution with specific assumptions such as infinitely long uniform plasma or a delta-function-like slab. In actual systems, however, RT is generally combined with other dynamics such as the density compression and formation of the two-step profile in the electron density. We derived a quasi-static solution of the laser field for two-step electron density, which occurs usually in the laser pulse and over-dense plasma interaction. Using our theory, we could calculate the radiation pressure, which pushes the front electron surface in hole-boring (HB) process. Therefore it was possible to predict the temporal evolution of the density more precisely. Moreover, the theory suggests a modified (actually improved) condition for the optimal thickness of the plasma target in RPA system. In this talk, we present some details of the theories and the comparison of the theories with one-dimensional particle-in-cell (1D PIC) simulation data.

10240-14, Session 3

Simulation study of electrostatic shock formation by a circularly polarized laser pulse

Young-Kuk Kim, Teyoun Kang, Min Sup Hur, Ulsan National Institute of Science and Technology (Korea, Republic of)

Collisionless electrostatic shock (CES) has received much attention in recent years because of energetic ion beam generation and feasible experimental conditions such as near-critical density plasma and PW-class laser system. The important conditions for shock formation are density compression and high temperature in the upstream in order to satisfy CES Mach number condition $1.5 < M < 3.7$, where $M=v/cs$ is Mach number, cs is the sound speed determined by temperature. In numerous former studies on CES, they used linearly polarized (LP) pulses, which were advantageous in heating the electrons in the upstream owing to the oscillating component of the ponderomotive force. In addition, relatively high density of the plasma was required to obtain strong compression of the plasma by increased reflectivity. We have lately suggested CES formation using a circularly polarized pulse (CP) in near-critical density plasmas. In the CP-driven shock, there is no oscillating component in the ponderomotive force for electron heating. Instead, relativistically transmitted pulse heats the electrons. Parametric one-dimensional simulation study shows that CP can generate shock in lower density plasma due to effective density compression. As the shock velocity is high in low density plasmas, more energetic ion beams can be obtained in comparison with LP-shock. The effective density compression by continuous ponderomotive force of CP results in fast shock formation, which leads the shock formation to be independent with plasma scale length. Moreover we observed that the filamentation (e.g. by Weibel instability) in two-dimensional systems is suppressed more by the CP pulses than the LP pulses. Consequently, a relatively clear shock structure could be obtained by CP pulses. This study would help to understand previous laser-driven ion acceleration simulations and experiments using an ultrashort pulse duration of order 30 fs.

10240-15, Session 3

Concerted manipulation of laser plasma dynamics and optimization with two laser pulses

Julia Braenzel, Alexander A. Andreev, Lutz Ehrentraut, Matthias Schnuerer, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

The acceleration of electrons in intense laser initiated fields is a promising way to obtain dense relativistic electron bunches, since localized light fields or the laser plasma interaction provide extreme acceleration gradients. The laser electron acceleration from solid dense targets is recently in the research focus, since it enables a scaling of the electron energy and particle number as a function of the laser intensity. In general, the energy gain of electrons in a laser field, as a fundamental physical question, is restricted by the following reasons: Electrons move collectively with the oscillating electro-magnetic laser field, gain energy but suffer again from a deceleration when the laser field decays. In order to enable a net gain of the kinetic energy from the laser field, the interaction has to be confined with specific boundary conditions. In this talk, we present experimental and theoretical results that reveal, how a decoupling between light field and electrons leads to a significant higher amount of fast electrons. With an laser intensity of 7x1019 W/cm2 and ultrathin foil targets we demonstrate, that slow electrons (keV) emitted from the ultrathin foil target are post-accelerated in the transmitted laser field. They were detected with significant higher kinetic energies (MeV), when this interaction was limited in duration. Decoupling we realized with a second separator foil, blocking the transient laser light at a particular distance. Model calculation of the experiment confirms our interpretation [1].

10240-16, Session 3

Accelerating gradient improvement using shape-tailor laser front in radiation pressure acceleration grogress

Wenpeng Wang, Shanghai Institute of Optics and Fine Mechanics (China)

The development of laser technology has allowed the intensity of a laser to be increased up to 10^22 W/cm^2. Energetic ions can be generated by irradiating solid foils with such an intense laser, which have potential applications to fast ignition for inertial confinement fusion, medical therapy, proton imaging, and so on. Several well-known mechanisms have been proposed to accelerate ions to high energies, such as collision-less shock acceleration at the target's front, target normal sheath acceleration at the target's back, and radiation pressure acceleration and laser-breakout afterburner acceleration for the whole target. Of these mechanisms, radiation pressure acceleration (RPA) has the highest efficiency, providing a promising mechanism for generating ions with a monoenergetic spectrum in the gigaelectronvolt range.

However, RPA also has intrinsic problems. For example, the accelerating progress is seriously limited by the development of Rayleigh–Taylor, Weibel, and other multidimensional instabilities. To address this problem, laser pulse shapes have been specially designed for RPA. Among the methods used, a sharp-front laser was proposed to quickly accelerate protons into the relativistic region. The main reason for this was the fact that the instabilities grow ? times slower as they move into the relativistic frame. It is beneficial that the era of the sharp-front laser will open with the future development of a 10 PW laser system. It is hoped that an extremely high intensity (~10^23–10^24 W/cm^2) can be realized by reducing the laser duration to 10-30 fs. At that time, efficient RPA will be realized. Obtaining the optimum RPA with a high accelerating gradient within such a short duration is a challenge that must be resolved.

In our work, a shape-tailored laser front is proposed to increase the accelerating gradient from the hole-boring (HB) to light-sail (LS) stage in the RPA region. The fastest ions initially resting in the middle of the foil are controlled to catch the compressed electron layer (CEL) at the end of the hole-boring stage, which allows the LS stage to begin as soon as possible. Then, the tightly compressed electron layer is accelerated along with the fastest ions by the shaped laser intensity, which further increases the accelerating gradient in the light-sail stage. Such a tailored pulse may be beneficial for the RPA with the future development of the high-intense laser.

10240-17, Session 4

Optimization of the electron beam properties from intense laser pulses interacting with structured gas jets *(Invited Paper)*

Kelly Swanson, Hai En Tsai, Samuel K. Barber, Remi Lehe, Hann-Shin Mao, Sven Steinke, Jeroen van Tilborg, Kei Nakamura, Cameron C. G. R. Geddes, Carl B. Schroeder, Eric H. Esarey, Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

Laser plasma accelerators (LPAs) are researched for their ability to produce acceleration gradients three orders of magnitude greater than those produced in conventional accelerators. Tailoring the plasma density profile allows control over the injection and acceleration processes, and plasma density downramp has been shown to be a promising injection mechanism. With a 1.8 J, 45 fs laser interacting with a shock-induced density downramp, we demonstrated that we can manipulate the electron beams through precision tailoring of the density profile produced by a gas jet and blade assembly. We investigated the effects of the density profile and of the shock front angle on beam parameters such as spatial profile, steering and absolute energy spread, both experimentally and with particle-in-cell simulations. Experimental data was explained using simple models, providing a better understanding of downramp injection. By adjusting the density profile parameters, we controlled the electron beam quality while independently tuning the energy (30-180 MeV) and energy spread (4-15 MeV). These techniques allow for high-quality electron beams with percent-level energy spread to be tailored based on the LPA application needs.

10240-18, Session 4

Probing plasma wakefield using femtosecond relativistic electron bunches *(Invited Paper)*

Wei Lu, Tsinghua Univ. (China)

Light-speed moving wakefield structure in a laser plasma accelerator is directly observed and quantitatively reconstructed using an ultrashort relativistic electron probe in a single shot. The stable electron probes utilized here are directly generated through laser wakefield acceleration via ionization injection. As the probe bunch traverses the wake, its momentum is modulated by the electric field of the wake, leading to a density variation of the probe after free-space propagation. From the density image of the probe, the local plasma wavelength, the wake width and the electric field in linear wakes can be accurately calculated, leading to the first observation of plasma wakes at the density as low as 1017 cm-3. Furthermore, detailed features of multiple wakes excited by a laser with the aberrated profile are observed and confirmed by 3D PIC simulations. By varying the time delay between the driving laser and the probe, time-resolved observation of the wake evolution (excitation, propagation, and damping) can be readily obtained, and this suggests that ultrafast electron probe can be a powerful new tool for the study of wakefield acceleration. The method is particularly well suited for visualizing linear wakefields that can accelerate both electrons and positrons as well as collective fields associated with shocks and instabilities in plasmas and warm dense matter.

10240-19, Session 4

Innovative single-shot diagnostics for electrons accelerated through laser-plasma interaction at FLAME

Fabrizio Bisesto, Istituto Nazionale di Fisica Nucleare (Italy)

Plasma based accelerators have been strongly studied in the last ten years in order to exploit the high accelerating gradients (hundreds of GV/m), achieving GeV class electron beams in few centimeters, thanks to the high power class laser system commercially available. In addiction, from the interaction between such lasers and solid targets, it is possible to accelerate positive charged particle (ions, protons) as well. Nevertheless, this kind of beams is really sensitive to the shot-by-shot instabilities (e.g. laser fluctuations). Therefore, it becames necessary to have single shot diagnostics to avoid meaningless statistical measurements.

At SPARC_LAB Facility in Frascati (Italy) the sub-PW class FLAME laser has been used to produce electrons by interacting with gas and metallic target aiming to test three different single shot longitudinal and transverse diagnostics: electro optics sampling (EOS) for temporal measurement, optical transition radiation (OTR).

In detail, the EOS technique has been employed to measure for the first time the longitudinal profile of electric field of fast electrons escaping from a solid target, driving the ions and protons acceleration, and to study the impact of using different shapes. On the other hand, a novel scheme for one shot emittance measurements based on OTR has been developed and tested at SPARC_LAB LINAC and an experiment on electrons from LWFA is currently undergoing.

10240-20, Session 4

High-quality electron beam generation and bright betatron radiation from a cascaded laser wakefield accelerator *(Invited Paper)*

Jiansheng Liu, Wentao Wang, Wentao Li, Rong Qi, Zhijun Zhang, Changhai Yu, Cheng Wang, Jiaqi Liu, Zhiyong Qing, Fang Ming, Yi Xu, Yuxin Leng, Ruxin Li, Zhizhan Xu, Shanghai Institute of Optics and Fine Mechanics (China)

One of the major goals of developing laser wakefiled accelerators (LWFAs) is to produce compact high-energy electron beam (e-beam) sources, which are expected to be applied in developing compact x-ray free-electron lasers and monoenergetic gamma-ray sources. Although LWFAs have been demonstrated to generate multi-GeV e-beams, to date they are still failed to produce high quality e beams with several essential properties (narrow energy spread, small transverse emittance and high beam charge) achieved simultaneously.

Here we report on the demonstration of a high-quality cascaded LWFA experimentally via manipulating electron injection, seeding in different periods of the wakefield, as well as controlling energy chirp for the compression of energy spread. The cascaded LWFA was powered by a 1-Hz 200-TW femtosecond laser facility at SIOM. High-brightness e beams with peak energies in the range of 200-600 MeV, 0.4-1.2% rms energy spread, 10-80 pC charge, and ~0.2 mrad rms divergence are experimentally obtained. Unprecedentedly high 6-dimensional (6-D) brightness B6D,n in units of A/m2/0.1% was estimated at the level of 1015-16, which is very close to the typical brightness of e beams from state-of-the-art linac drivers and several-fold higher than those of previously reported LWFAs.

Furthermore, we propose a scheme to minimize the energy spread of an e beam in a cascaded LWFA to the one-thousandth-level by inserting a stage to compress its longitudinal spatial distribution via velocity bunching. In this scheme, three-segment plasma stages are designed for electron injection, e-beam length compression, and e-beam acceleration, respectively. A one-dimensional theory and two-dimensional particle-in-cell simulations have demonstrated this scheme and an e beam with 0.2% rms energy spread and low transverse emittance could be generated without loss of charge.

Based on the high-quality e beams generated in the LWFA, we have experimentally realized a new scheme to enhance the betatron radiation via manipulating the e-beam transverse oscillation in the wakefield. Very brilliant quasi-monochromatic betatron x-rays in tens of keV with significant enhancement both in photon yield and peak energy have been generated. Besides, by employing a self-synchronized all-optical Compton scattering scheme, in which the electron beam collided with the intense driving laser pulse via the reflection of a plasma mirror, we produced tunable quasi-monochromatic MeV ?-rays (33% full-width at half-maximum) with a peak brilliance of ~3.1?1022 photons s-1 mm-2 mrad-2 0.1% BW at 1 MeV, which is one order of magnitude higher than ever reported value in MeV regime to the best of our knowledge.

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10240-21, Session 4

Energy spread minimization in a cascaded laser wakefield accelerator via velocity bunching

Zhijun Zhang, Shanghai Institute of Optics and Fine Mechanics (China)

We report the observation of energy-spread compensation of electron bunches in a laser wakefield accelerator in experiment. The compensation was caused by the gradient wakefield in plasma wake, and the energy spectra of the bunches evolved during the acceleration so that we propose a new method to diagnose the longitudinal length of the ultrashort electron bunch. By analyzing the energy spectra of electron bunches with different acceleration length, the wakefield gradient difference and the wakefield slope of the bunch could be estimated by combining with the slippage between the plasma wave and the electron bunch, thus the electron bunches? longitudinal length could be estimated. By applying this new method, the longitudinal length of electron bunches with charge of about 40 pC generated from a laser wakefield accelerator was estimated to be (2.4 ± 2.2) ?m in experiment, which was in good agreement with three-dimension particle-in-cell simulations.

10240-22, Session 5

Application of a laser heater for enhanced guiding of tightly focused laser pulses at low densities *(Invited Paper)*

Joost Daniels, Lawrence Berkeley National Lab. (United States) and Technische Univ. Eindhoven (Netherlands); Anthony J. Gonsalves, Lawrence Berkeley National Lab. (United States); Christopher V. Pieronek, Lawrence Berkeley National Lab. (United States) and Univ. of California, Berkeley (United States); Carlo Benedetti Jr., Carl B. Schroeder, Stepan S. Bulanov, Hann-Shin Mao, Kei Nakamura, Eric H. Esarey, Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

In the field of laser-plasma accelerators (LPAs), increasing the energy of the output particle bunches requires increased transfer of energy from the incident laser pulse to the plasma. In many current LPA schemes, this is done by guiding focused laser pulses by a plasma channel. Such a plasma channel can be created by a high voltage discharge in a gas-filled capillary. This method has yielded electron beam energies of up to 4.2 GeV on the BELLA system [1]. In order to improve upon this result, a lower plasma density is required to prevent dephasing (and the resulting deceleration) of the electrons with respect to the plasma wave. At the densities required, the waveguide will be weaker, causing a mismatch with the fixed laser spot size. This results in strong oscillations of driver laser intensity in the channel along the axis. A proposed solution to this issue is through localized inverse Bremsstrahlung heating with a separate, ns-scale laser pulse [2]. This heater pulse deepens the channel to confine the driver pulse and to maintain high driver intensity along the length of the channel. We show that in combination with a longer channel it is possible to reach beam energies beyond 8 GeV.

In a proof-of-principle experiment, plasma heating by means of a 10 ns-scale laser was observed. Furthermore, we have demonstrated confinement of a low-energy ultrashort pulse, with control of the channel size by varying the delay between the pulses on the ns timescale. In this talk, we will present the latest results in employing this technique on the BELLA PetaWatt system, including tuneability of the waveguide and the effect at higher driver laser energies. This research represents the state-of-the-art in the development of single-stage accelerator modules capable of producing 10 GeV electron beams with meter-scale plasmas.

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10240-23, Session 5

Nested Rogowski coils for measuring the electron densities of a laser driven plasma in a capillary

Johannes Grunwald, Danila Khikhlukha, Dariusz Kocon, Lukas Pribyl, ELI Beamlines (Czech Republic)

Rogowski coils have been used to diagnose high energetic electron beams since the seventies of the last century [1-4] but usually these measurements were restricted to a single point on the beam axis.

This poster presents a new experimental concept to measure the axial and radial electron density profiles of the laser-accelerated plasma created in a capillary. We propose to use nested arrays of Rogowski coils to measure the current contributions parallel and normal to the driving laser beam with a spatial resolution in the mm range. 3-D CAD models of the experimental setup are presented along with first numerical simulations of the field gradients, which are to be expected within the coils. The particle-in-cell (PIC) code simulations were performed to obtain the electron density profile within the plasma channel. From these results the currents and, hence, the field gradients were deduced. The tilted 90 degrees with respect to the capillary axis while the outer one will be coaxial to the plasma channel. The main advantages of this plasma diagnostics method are the simplicity and robustness of the setup as well as the fact that it is a passive measurement technique, which has no influence on the plasma itself. Furthermore, the reliance of such coils on a Biot-Savart inductivity allows to distinguish the contributions of the parallel and perpendicular current (i.e. only the current components parallel to the direction of motion of the charge carriers is picked up by the coils). As Rogowski coils do not have a ferromagnetic core, non-linear effects resulting from such a core can be omitted as well, which increases the reliability of the obtained data. They also allow to measure fast signals that carry high currents (up to several hundred kA).

References:

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10240-25, Session 5

Wide-angle electron beams from laser-wakefield accelerators

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Advances in laser technology have driven the development of laser-wakefield accelerators, compact devices capable of accelerating electrons to GeV energies over cm-distances by exploiting the strong electric field gradients arising from the interaction of intense laser pulses with an underdense plasma. A side-effect of this acceleration mechanism is the production of high-charge, low-energy electron beams at wide angles. Here we present an experimental and numerical study of the properties of these wide-angle electron beams, showing that the energy they carry can be a significant fraction of the energy transferred from the laser to the plasma. These high-charge, wide-angle beams can also cause damage to laser-wakefield accelerators based on capillaries, as well as become source of unwanted bremsstrahlung radiation.

10240-26, Session 6

Acceleration of relativistic electrons with kiloHertz single-cycle laser pulses *(Invited Paper)*

Jérôme Faure, Diego Guénot, Lab. d'Optique Appliquée (France); Dominykas Gustas, Lab. d'Optique Appliquée (France); Aline Vernier, Benoît Beaurepaire, Frederik Böhle, Lab. d'Optique Appliquée (France); Rodrigo López-Martens, Lab. d'Optique Appliquée (France); Agustin Lifschitz, Lab. d'Optique Appliquée (France)

Laser-plasma accelerators are usually driven by 100-TW class laser systems with rather low repetition rates. However, recent years have seen the emergence of laser-plasma accelerators operating with kHz lasers and energies lower than 10 mJ. The high repetition-rate is particularly interesting for applications requiring high stability and high signal-to-noise ratio but lower energy electrons. For example, our group recently demonstrated that kHz laser-driven electron beams could be used to capture ultrafast structural dynamics in Silicon nano-membranes via electron diffraction with picosecond resolution. In these first experiments, electrons were injected in the density gradients located at the plasma exit, resulting in rather low energies in the 100 keV range. The electrons being nonrelativistic, the bunch duration quickly becomes picosecond long. Relativistic energies are required to mitigate space charge effects and maintain femtosecond bunches.

In this paper, we will show very recent results where electrons are accelerated in laser-driven wakefields to relativistic energies, reaching up to 5 MeV at kHz repetition rate. The electron energy was increased by nearly two orders of magnitude by using single-cycle laser pulses of 3.5 fs, with only 2.5 mJ of energy. Using such short pulses of light allowed us to resonantly excite high amplitude and nonlinear plasma waves at high plasma density, ne=1.5-2?1020 cm-3, in a regime close to the blow-out regime. Electrons had a peaked distribution around 5 MeV, with a relative energy spread of ~30 %. Charges in the 100's fC/shot and up to pC/shot where measured depending on plasma density. The electron beam was fairly collimated, ~20 mrad divergence at Full Width Half Maximum. The results show remarkable stability of the beam parameters in terms of beam pointing and electron distribution. 3D PIC simulations reproduce the results very well and indicate that electrons are injected by the ionization of Nitrogen atoms, N5+ to N6+, leading to the formation of an electron bunch of 1 fs duration.

The interaction of single-cycle pulses with the plasma also leads to new physical effects. We have observed experimental evidence that plasma dispersion cannot be neglected in this regime. This is due to the extremely broad bandwidth of the laser, extending from 400 nm to 1000 nm, and to the high electron density. Therefore, the acceleration process is optimal when small positive chirps are introduced: the negative dispersion of the plasma then causes the re-compression of the laser pulse inside the plasma. Simulations indicate that this help localizing the injection process, leading to single femtosecond electron bunch.

Such a kHz femtosecond electron source will pave to way to numerous innovative applications, such as sub-10 fs electron diffraction, radiolysis of water with unprecedented resolution or the generation of femtosecond X-ray at kHz.

10240-27, Session 6

Laser-driven electron beam generation for secondary photon sources with few terawatt laser pulses

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Femtosecond laser pulses interacting with underdense plasma were shown to be a promising technique of ionizing particle generation. Relativistic electron beams accelerated by laser wakefield have the ability to serve as sources of collimated, point-like and femtosecond X-ray radiation. These secondary photon sources are now of a great interest at short-pulse high-power laser facilities.

The purpose of our work was to optimize conditions necessary for building this type of electron and X-ray source in a small laboratory equipped with a common femtosecond

few-terawatt laser. Production of quasi-monoenergetic electrons is important for generation of stable betatron radiation and X-ray pulses from inverse Compton scattering.

In our experiment, the laser pulse with the duration of 50 fs and the energy of 600 mJ was used for the electron acceleration. Various gas jet targets, such as helium, a mixture of helium and argon, a mixture of helium and nitrogen, and dry air, were employed for this purpose and the obtained results are compared. The approach to use dry air was previously proven to be an inexpensive gas jet option allowing generation of electron beams that are stable in energy and energy spread. Moreover, this type of target allows to lower the costs of the electron and X-ray source and its operation. In order to increase the applicability for medical purposes and various novel imaging techniques, the source was operated under the repetition rate of >1 Hz.

The accelerator was operated in bubble regime with forced self-injection and resulted in the generation of stable relativistic electron beams with an energy of up to a hundred MeV; betatron X-ray radiation and radiation from inverse Compton scattering were generated in the keV range. A razor blade was used to create a steep density gradient in order to improve the stability of electron injection and to increase the total electron bunch charge. Furthermore, custom 3D-printed gas jet nozzles were tested in order to achieve the optimum plasma parameters, such as electron plasma density.

It was proven that the stable electron and X-ray source can be built even at small-scale facilities equipped with a few terawatt femtosecond laser system and is thus suitable for various applications. Simulations and experimental results are presented.

10240-28, Session 6

First experimental results from the LUX Beamline for plasma-driven undulator radiation

Andreas R. Maier, Univ. Hamburg (Germany)

We discuss the commissioning and present first experimental results from the LUX Beamline for plasma-driven undulator radiation. This beamline is build within a close collaboration of the University of Hamburg and DESY, combining university research with the tools, philosophy and expertise of a large accelerator facility as a sound basis for robust performance for applications.

10240-29, Session 6

High quality electron bunch production for high brilliance sources

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Laser Wake Field accelerated electrons need to exhibit a good beam-quality to comply with requirements of FEL or other high brilliance sources, or to be post-accelerated in a further LWFA stage towards TeV energy scale. Controlling electron injection, plasma density profile and laser pulse evolution are therefore crucial tasks for high-quality e-bunch production.

We are implementing a dedicated LWFA scheme using our new 250 TW 25fs Ti:Sa laser installation . In the talk we will present our latest results on the design of a multi-GeV scale, low energy spread, low emittance bunch generation based on controlled-injection schemes in a weakly nonlinear LWFA regime with guiding.

Two bunch injection mechanisms will be described, namely the density down-ramp injection and ionization injection.

Since wakefield wavelength must be almost constant within all the acceleration length so as to minimize nonlinear phase oscillation, pulse propagation should result in a stable envelop evolution. Matching between the injected laser pulse and the preformed plasma channel is therefore a crucial task for final high-quality beam-quality purposes.

We will therefore report on plasma longitudinal/radial profiles requirements to achieve stable sub-PW pulse evolution in tens-cm scale preformed plasma.

Finally, an overview of the new ILIL-PW installation and the status of the LWFA experiments will also be given.

10240-30, Session 6

Laser high-harmonic generation in cavitated plasma wakefields

Carl B. Schroeder, Carlo Benedetti Jr., Eric H. Esarey, Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

Coherent x-ray light sources are of interest for many applications. Laser high-harmonic generation (HHG) is a compact method for producing ultrafast, coherent light, but is limited to the extreme-ultraviolet to soft-x-ray spectral region. In HHG, an ultrashort intense laser is focused into a gas, generating multi-harmonics of the laser frequency. Physically, harmonics are generated by bound atomic electrons that tunnel through the effective potential barrier formed by the atom and laser field, oscillate semi-classically in the laser field, and recombine with the atom, emitting a high-energy photon. Photon energies up to keV have been produced via HHG. Hard x-ray generation is suppressed by ionization and plasma production, limiting the coherence length via plasma-induced phase slippage. Phase-matching to overcome the plasma-induced slippage has been a challenge to further development of HHG x-ray sources.

It this presentation a method for producing hard x-rays via high-harmonic generation using intense lasers is discussed. This method relies on plasma cavitation by an intense drive beam, producing a region without plasma electrons and with ions in a high-charge state, but not fully stripped of bound electrons. An ultra-short pulse laser co-propagating in the plasma-electron-free ion cavity generates laser harmonics. A charged-particle beam driver has been previously considered for ion cavity creation for HHG [Schroeder et al., Phys. Plasmas 15, 056704 (2008)]. In this presentation two laser pulses of different colors are considered: a long wavelength pulse to create an electron free ion cavity, and a short wavelength pulse to generate harmonics via interaction with the deeply-bound electrons. This method enables laser harmonic generation in the sub-nm regime. Examples of hard-x-ray HHG using existing and future laser systems will be presented.

10240-31, Session 7

Direct laser acceleration of electrons from underdense plasma channeling using picosecond laser pulses *(Invited Paper)*

Louise Willingale, Lancaster Univ. (United Kingdom); Alexey Arefiev, The Univ. of Texas at Austin (United States); Thomas G. Batson, Amina Hussein, Univ. of Michigan (United States); Philip M. Nilson, Lab. for Laser Energetics, Univ. of Rochester (United States); Hui Chen, Lawrence Livermore National Lab. (United States); Robert S. Craxton, T. Craig Sangster, Daniel Habergerger, Lab. for Laser Energetics, Univ. of Rochester (United States); Calvin A. Zulick, U.S. Naval Research Lab. (United States); Karl M. Krushelnick, Univ. of Michigan (United States)

A picosecond duration, relativistically intense laser pulse interacting with an underdense plasma is a complex process that can lead to the acceleration of a relativistic super-ponderomotive (up to 300 MeV) electron beam. Experiments performed on the OMEGA EP laser facility have investigated a variety of plasma density profiles and peak electron densities to optimize the electron acceleration using picosecond duration laser pulses. Solid foil targets are heated to form underdense plasma plumes in a variety of configurations to create different conditions. Proton and optical probing observe the electromagnetic fields and electron densities associated with the channel formation. Particle-in-cell simulations reveal the complex dynamics and different electron acceleration mechanisms that are likely contributing to the broad energy spectrum, high-charge, electron beam. These electron beams have potential to generate an extremely bright, directional, broadband x-ray source or for designing a test for the two-photon Breit-Wheeler process.

10240-32, Session 7

Research towards hybrid accelerators *(Invited Paper)*

Max F. Gilljohann, Hao Ding, Johannes Götzfried, Sabine Schindler, Ludwig-Maximilians-Univ. München (Germany); Johannes Wenz, Matthias Heigoldt, Konstantin Khrennikov, Ludwig-Maximilians-Univ. München (Germany) and Max-Planck-Institut für Quantenoptik (Germany); Simon M. Hooker, Univ. of Oxford (United Kingdom); Andreas S. Döpp, Ludwig-Maximilians-Univ. München (Germany); Stefan Karsch, Ludwig-Maximilians-Univ. München (Germany) and Max-Planck-Institut für Quantenoptik (Germany)

Beam-driven wakefield accelerators deliver accelerating fields in the order of 100 GV/m, but the requirements on charge and beam duration of the particle driver are challenging for conventional accelerators, and the requirements are met by only a few large-scale accelerators worldwide. However, electron beams from a laser-plasma accelerator are usually inherently well suitable as drivers, which potentially allows studying the physics of beam-driven wakefield acceleration in small-scale laser-facilities, in the future.

We present the observation of laser-accelerated electron bunches driving their own wakefields, which is a first step towards a table-top hybrid accelerator. The experiment is performed using the ATLAS 300 laser located at the LEX Photonics facility at LMU Munich. The Ti:Sa laser delivers 10 J with 28 fs pulses duration. Focused on a 3-5 mm hydrogen gas target we observe bunch charges of up to 1 nC with 400 MeV peak energy, from which we directly imaged the electron-driven wakefields in a second gas jet using a transverse probe beam with a duration of less than 10 fs.

Furthermore, we demonstrate a technique to generate a witness bunch with tunable separation to the driver which allows probing the wakefield. In addition to the shock-front of a blade inserted into a supersonic gas jet we utilize a counter-propagating laser beam to inject a second bunch through optical injection. The separation between these bunches ca be tuned with changing the separation of the two points of injection. The shock-front usually serves as the point of injection for the driver, and the optical injection for a witness-bunch with lower charge.

10240-33, Session 7

Plasma acceleration activities at SPARC_LAB.

Maria Pia Anania, Istituto Nazionale di Fisica Nucleare (Italy)

Plasma wakefield acceleration is the most promising acceleration technique known nowadays, able to provide very high accelerating fields (10–100 GVm?1), enabling acceleration of electrons to GeV energy in few centimetres. Here we present all the plasma related activities currently underway at SPARC_LAB both using the high power laser FLAME and the LINAC. In particular, we will give an overview of all the experiments performed with the FLAME system, passing from the electron acceleration by LWFA to TNSA. We will then discuss the possibility to combine high brightness electron bunches from conventional accelerators and high accelerating fields reachable with plasmas which could be a good compromise allowing to further accelerate high brightness electron bunches coming from the SPARC_LAB LINAC while preserving electron beam quality (plasma wave resonant excitation driven by a train of short electron bunches). Eventually, we will discuss the external injection scheme, allowing the possibility to accelerate high brightness electron bunches accelerated by a LINAC with the high accelerating field generated by a high power laser in a plasma and in particular we will show the current status of the experiment at SPARC_LAB.

10240-34, Session 8

Ultra-intense lasers with high orbital angular momentum for structured wakefield excitation *(Invited Paper)*

Jorge M. Vieira, Instituto Superior Técnico (Portugal)

Plasma accelerators and associated light sources are a novel technology with the potential to drastically reduce the cost and size of conventional devices. Instead of using radio-frequency cavities, plasma accelerators employ relativistic plasma waves to accelerate particles to high energies. A unique property of plasma wakefields is that they can be shaped nearly arbitrarily. Because the wakefield results from the collective motion of electrons, we can access this topological freedom of the plasma by controlling the individual trajectories of plasma electrons. With theoretical modelling and massively parallel particle-in-cell (PIC) simulations using the PIC code Osiris, we will investigate the properties of structured plasma waves that can contain orbital angular momentum. We will explore the relation between the angular momentum of the wave with the microscopic angular momentum associated with the trajectories of plasma electrons. In addition, by examining the field structure of these plasma waves, we will determine the corresponding trapping conditions and acceleration properties [1]. Accessing the topological freedom of the plasma requires structured laser pulse drivers. We will discuss possible plasma-based mechanisms to create, amplify and gain unprecedented control over the spatiotemporal properties of structured laser pulses. We propose to use stimulated Raman scattering in the plasma to compress and amplify lasers with exotic spatiotemporal field profiles like orbital angular momentum [2]. In addition, we will also show that Stimulated Raman scattering can be used to create high orbital angular momentum harmonics independently of any other laser property, such as the laser frequency. We will illustrate our findings with three-dimensional Osiris simulations illustrating the production of ultra-intense lasers with very high degrees of orbital angular momentum [3]. Our findings could also be tested in nonlinear optical Kerr media.

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10240-35, Session 8

Dynamics of boundary layer electrons around a laser wakefield bubble

Min Chen, Shanghai Jiao Tong Univ. (China)

The dynamics of electrons forming the boundary layer of a highly nonlinear laser wakefield is investigated using computational simulations. It is shown that when the driver pulse intensity increases or the focal spot size decreases, a significant amount of electrons initially pushed by the laser pulse can detach from the bubble structure at its tail, middle, or front and form particular classes of waves locally with high densities, referred to as the tail wave, lateral wave, and bow wave. Simulation results show that the tail and bow waves correspond to real electron trajectories, while the lateral wave does not. The detached electrons can be ejected transversely, containing considerable energy, and reducing the efficiency of the laser wakefield accelerator. Some of the transversely emitted electrons may obtain MeV level energy. These electrons can be used for wake evolution diagnosis and producing high frequency radiation.

10240-36, Session 8

High-brightness high-energy electron beams from a laser wakefield accelerator via energy chirp control

Wentao Wang, Shanghai Institute of Optics and Fine Mechanics (China)

By designing a structured gas density profile between the dual-stage gas jets to manipulate electron seeding and energy chirp reversal for compressing the energy spread, we have experimentally produced high-brightness high-energy electron beams from a cascaded laser wakefield accelerator with peak energies in the range of 200-600 MeV, 0.4%-1.2% rms energy spread, 10-80 pC charge, and ?0.2??mrad?rms divergence. The maximum six-dimensional brightness B_{6D,n} is estimated as ?6.5?10^{15}??A/m^{2}/0.1%, which is very close to the typical brightness of e beams from state-of-the-art linac drivers. These high-brightness high-energy e beams may lead to the realization of compact monoenergetic gamma-ray and intense coherent x-ray radiation sources.

10240-37, Session 8

Short energetic electron bunches from laser wakefield accelerator with orthogonally polarized perpendicularly crossed laser beams

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The optical injection of the electrons into the ion cavity in the bubble regime of the laser wakefield acceleration by a perpendicularly propagating and transversely polarized low intensity laser beam is numerically studied. Accelerated electron bunches provide a higher energy, the lower energy spread, and the injected charge of the same order of magnitude for the standard bubble regime parameters compared to other proposed schemes of optical injection such as the counter-propagating 2-pulse scheme. Furthermore, thanks to the fact that the injection pulse intensity is in order of hundredths of the drive pulse intensity, the bubble dynamics is not disturbed significantly.

The bunch of accelerated electrons gains a rather large energy with a low energy spread on the short acceleration distances. Large energy interval separates optically injected electron bunch from lower energy electrons accelerated in secondary bubbles. However, the transverse emittance of generated electron bunch is rather higher in this case.

The simulations also show that the maximum energy of produced electron bunches is almost independent of the short injection pulse delay. However, the maximum charge is generated when both pulse centres overlap. Moreover, the simulations reveal that the injection pulse should be focused to the similar size as drive pulse. The increase in the ratio of intensities of the injection and drive pulses results in a larger energy spread, the decrease in maximum energy and a small enhancement of the bunch charge.

Our simulations also show strong electron heating during the beam collision. The optically injected energetic electron bunch only appears when the velocity of some electrons accelerated during the beam collision is equal or larger than the group velocity of the laser beam and of the corresponding wake wave. This implies that the stochastic heating during the laser pulses collision can be the cause of injection for low amplitudes of the injection pulse.

X-ray betatron radiation is produced due to transverse electron oscillations in the ion cavity. Supplementary numerical simulations taking into account generated bunch properties indicate that the X-ray pulse has appropriate features, i.e. it is shorter and it has a higher critical energy than in other schemes of optical injection or self-injection.

10240-38, Session 8

Intrinsic elimination of the numerical Cherenkov instability in Lorentz-boosted frame simulations of plasma accelerators

Manuel Kirchen, Univ. Hamburg (Germany)

We present a novel Particle-in-Cell algorithm that is intrinsically free of the numerical Cherenkov instability for relativistic plasmas flowing at a uniform velocity. The new method is independent of the geometry and - unlike previous suppression strategies - we completely avoid artificial modifications of the electromagnetic fields. Application is shown at the example of Lorentz-boosted frame simulations of plasma accelerators, achieving excellent accuracy and high speed-ups using our spectral, quasi-3D GPU code FBPIC.

10240-39, Session PS

The error analysis for laser wakefield acceleration simulations

Danila Khikhlukha, ELI Beamlines (Czech Republic); Niels Delbos, Ctr. for Free-Electron Laser Science (Germany); Vincent Leroux, Ctr. for Free-Electron Laser Science (Germany) and The Czech Academy of Sciences (Czech Republic); Lukas Pribyl, The Czech Academy of Sciences (Czech Republic); Andreas R. Maier, Ctr. for Free-Electron Laser Science (Germany)

The laser-driven Undulator X-ray source (LUX) is designed to be a user beamline providing ultra-short EUV photon pulses in a water window region and a peak brilliance of up to 10^21 photons/(s.mrad2.mm2.0.1% B.W.), which makes this source comparable with modern synchrotron sources. The source shall provide a focal spot size well below 10 ?m and a range of auxiliary beams for complex pump-and-probe experiments

and it is also an important experimental milestone towards a future laser driven Free Electron Laser.

Recently the initial LUX beam line setup accelerated its first electrons ever. To assist the further development of the beam line towards it's design parameters, in this paper we shall present a comparison between experimentally measured accelerated electrons properties and simulations. In particular a beam energy and beam energy spread, measured with a scintillating LANEX screen, are examined against the computed values. The plasma simulations were done by means of particle-in-cell method. To achieve better agreement,the measured focal spot intensity and phase distributions were used as an input for the simulation. The hydrogen pressure profile along the capillary's axis was simulated for the particular target geometry and was also incorporated in the plasma calculations.

We report the results of systematic and random errors analysis. The numerical stability of simulation results as well as variations in the experimental data have been studied. We also discuss the possible source of systematic errors.

10240-40, Session PS

X-ray phase contrast imaging of biological samples using a pulsed X-ray generated in a compact laser wakefield accelerator

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Phase contrast X-ray imaging (PCI) offers superior image quality to the conventional x-ray radiography for detecting the small structures in soft tissues having homogeneous absorption profile. It requires a bright and sufficiently small X-ray source with high spatial coherence at the object position. The conventional X-rays from synchrotron facilities produce X-ray source with high brightness and are the ideal source for phase contrast imaging, but access to these facilities is very limited. The betatron X-rays, generated in laser wakefield acceleration (LWFA) has a micrometric source size, a high peak spectral brightness, ultra-short duration, is very suitable for such imaging contrary to the conventional X-ray in which the source size is of the order of mm. For the microscopic scale resolution phase contrast imaging, propagation-based phase contrast is a suitable one.

We have performed propagation-based phase contrast imaging of biological samples using the betatron X-ray source generated in LWFA scheme. The experiments were performed at Salle Jaune, LOA, Ecole Polytechnique, France. The X-rays were generated in LWFA scheme, in which the laser (t = 30 fs, wavelength = 800 nm) is focused at the entrance of a supersonic de Laval nozzle gas jet (He or gas mixture (99% He + 1% Ne)) of 3 mm diameter using an off-axis parabolic mirror delivering an energy of about 1.2 J on the target. The laser-plasma accelerator was operated in the self-injection regime, producing an electron beam with energies mostly in the range of 100–150 MeV, and the betatron radiation with a critical energy of about 6.5 keV. The betatron X-ray source size was measured about 2 ?m. We used this source to perform X-ray phase contrast imaging of different biological samples. We will present the results of high contrasts phase contrast imaging of the biological samples.

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10240-41, Session PS

Requirements on the LWFA electron beam for the user-oriented photon source

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The laser-driven Undulator X-ray source (LUX) is designed to be a user beamline providing ultra-short EUV photon pulses with a central wavelength tuneable in the range of 0.4 to 4.5 nm and a peak brilliance of up to 1e21 photons/(s.mrad2.mm2.0.1% B.W.), which makes this source comparable with modern synchrotron sources. The source shall provide a focal spot size well below 10 ?m and a range of auxiliary beams for complex pump-and-probe experiments and it is also an important experimental milestone towards a future laser driven Free Electron Laser.

Unique femtosecond nature of the laser-plasma electron acceleration in combination with extremely small transverse emittance of the electron beam is the major advantage of the LWFA technique. Preservation of the electron beam quality is a complicated task for a dedicated electron beam line, which has to be designed to transport the electron beam from the LWFA source up to the undulator. In this report we discuss main requirements on the LWFA source and the electron beam optics of the LUX source and solutions to produce required quality photon beam in the undulator and we also discuss the effect of realistic setup parameters on the quality of the electron beam in the undulator within the range of systematic errors.

10240-43, Session PS

Toward 10-GeV laser electron acceleration using 4 PW laser pulses

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The laser wakefield acceleration (LWFA) is one of the most attractive methods for next generation electron accelerators because it provides huge acceleration field larger by three orders of magnitude than that of conventional rf accelerators. The development of PW lasers has prompted the investigation of a new regime in laser electron acceleration. We have developed two PW Ti:Sapphire laser beamlines [1], and successfully applied the PW laser pulses to generate a 3-GeV electron beam [2]. Recently, we demonstrated a new method to stabilize multi-GeV electron beams by controlling the waveform of PW laser pulses. At CoReLS, we have upgraded one of the PW laser beamlines to a 20-fs, 4-PW laser, which can offer opportunities to achieve a 10-GeV electron beam and to explore QED effects in nonlinear Compton backscattering process. We present the plan for producing 10-GeV electron beam driven by the 4-PW laser and for performing experiments on all-optical nonlinear Compton back scattering using 1 PW and 4 PW lasers. These developments of high energy electron beam and all-optical Compton scattering with multi-PW lasers will open a route to examine radiation reaction mechanism and QED effects in photon-electron interactions.

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10240-44, Session PS

Direct acceleration in intense laser fields used for bunch amplification of relativistic electrons

Julia Braenzel, Alexander A. Andreev, Lutz Ehrentraut, Matthias Schnuerer, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

The acceleration of electrons in intense laser initiated fields is a promising way to obtain dense relativistic electron bunches, since localized light fields or the laser plasma interaction provide extreme acceleration gradients. The laser electron acceleration from solid dense targets is recently in the research focus, since it enables a scaling of the electron energy and particle number as a function of the laser intensity. In general, the energy gain of electrons in a laser field, as a fundamental physical question, is restricted by the following reasons: Electrons move collectively with the oscillating electro-magnetic laser field, gain energy but suffer again from a deceleration when the laser field decays. In order to enable a net gain of the kinetic energy from the laser field, the interaction has to be confined with specific boundary conditions. In this talk, we present experimental and theoretical results that reveal, how a decoupling between light field and electrons leads to a significant higher amount of fast electrons. With an laser intensity of 7x1019 W/cm2 and ultrathin foil targets we demonstrate, that slow electrons (keV) emitted from the ultrathin foil target are post-accelerated in the transmitted laser field. They were detected with significant higher kinetic energies (MeV), when this interaction was limited in duration. Decoupling we realized with a second separator foil, blocking the transient laser light at a particular distance. Model calculation of the experiment confirms our interpretation [1].

[1] J. Braenzel et al. Phys. Rev. Lett., in press.

Conference 10241: Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers

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10241-1, Session 1

The future action of ELI under the ERIC umbrella *(Invited Paper)*

Carlo Rizzuto, Elettra-Sincrotrone Trieste S.C.p.A. (Italy) and Extreme Light Infrastructure Delivery Consortium International (Belgium)

No Abstract Available

10241-2, Session 1

ELI Beamlines: status of user facility development *(Invited Paper)*

Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

We will be giving an overview on the development of the "ELI-beamline facility" being built within the Extreme Light Infrastructure (ELI) project based on the European ESFRI (European Strategy Forum on Research Infrastructures) process.

ELI-Beamlines will be a high-energy, repetition-rate laser pillar of the ELI (Extreme Light Infrastructure) project. It will be an international facility for both academic and applied research, slated to provide user capability since the beginning of 2018. The main objective of the ELI-Beamlines Project is delivery of ultra-short high-energy pulses for the generation and applications of high-brightness X-ray sources and accelerated particles. The laser systems will be delivering pulses with length ranging between 10 fs and 150 fs and will provide high-energy Petawatt and 10-PW peak powers. For high-field physics experiments it will be able to provide focused intensities attaining >1022-23 Wcm-2, while this value can be increased in a later phase without the need to upgrade the building infrastructure to go to the ultra-relativistic interaction regime in which protons are accelerated to energies comparable to their rest mass energy on the length of one wavelength of the driving laser.

We will discuss the status of the building and its infrastructure concerning the availability of experimental areas, the development of the lasers including highly stable beam transport solutions and secondary sources of particles and x-rays in the wavelength range between 20 eV-100 keV and their practical implementation in the ELI-Beamline user facility. The sources are either based on direct interaction of the laser beam with a gaseous targets (high order harmonics) or will first accelerate electrons which then will interact with laser produced wigglers (Betatron radiation) or directly injected into undulators (laser driven LUX or later X-FEL). The direct interaction (collision) of laser accelerated electrons with the laser again will lead to short pulse high energy radiation via Compton or Thomson scattering. The planned first commissioning experiments on x-ray generation, particle acceleration (electrons and protons) as well as on plasma physics and their applications together with the available experimental infrastructure will be introduced.

Two new projects ELI Bio and HIFI which have been funded recently will be introduced. The ELIBIO project explores new frontiers in light and optics to create breakthrough science in biology, chemistry, and physics whereas the HIFI project investigates ultra-intense laser plasma and laser vacuum interactions.

10241-3, Session 1

Status of ELI-ALPS implementation *(Invited Paper)*

Károly Osvay, Dimitris Charalambidis, Patrizio Antici, Péter Dombi, Lajos J. Fulop, Franck Lepine, Gergo Mészáros, Giuseppe Sansone, Katalin G. Varju, ELI-HU Nonprofit Kft. (Hungary)

The major research equipment of the Attosecond Light Pulse Source of the Extreme Light Infrastructure (ELI-ALPS) are driven by laser pulses of few cycle duration operating in the 100 W average power regime. The peak power and the repetition rate span from 1 TW at 100 kHz up to PW at 10 Hz. The systems are designed for stable and reliable operation, yet to deliver pulses with unique parameters, especially with unmatched fluxes and extreme bandwidths. This exceptional performance will enable the generation of secondary sources with exceptional characteristics, including light sources ranging from the THz to the X-ray spectral ranges, and particle sources.

The experimental activities in the building complex to be inaugurated early 2017 will start with the installation of the two 100 kHz repetition rate, CEP stabilized lasers in May 2017. The MIR laser produces 0.15mJ, shorter than 4-optical-cylce pulses tunable between 2.5-3.9 µm. The first stage of the HR laser will provide pulses around 1 µm with 1 mJ energy and pulse duration less than 6.2 fs. The systems will be optically synchronized to each other with a temporal jitter below 1 fs.

Along with the installation of the lasers, we will also start the assembly of the high harmonic beamlines and the THz laboratory, as well as nanoplasmonic experiments. The XUV bursts of light with attosecond duration are expected to be generated by the end of 2017.

10241-4, Session 1

Status of the construction of the 2x10PW laser system at ELI-NP *(Invited Paper)*

Daniel Ursescu, National Institute for Laser, Plasma and Radiation Physics (Romania)

No Abstract Available

10241-5, Session 1

Latest results from BELLA *(Invited Paper)*

Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

No Abstract Available

10241-6, Session 2

Extreme Light: going beyond the horizon

Jonathan Wheeler, École Polytechnique (France)

No Abstract Available

10241-7, Session 2

Ultraintense lasers and beams: plasmas at the extreme *(Invited Paper)*

Luis O. Silva, Instituto Superior Técnico (Portugal)

No Abstract Available

10241-8, Session 2

Simulate what is measured: next steps towards predictive simulations *(Invited Paper)*

Michael Bussmann, Thomas Kluge, Alexander Debus, Axel Hübl, Marco Garten, Malte Zacharias, Jan Vorberger, Richard Pausch, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); René Widera, Helmholtz-Zentrum Dresden-Rossendorf e.V. (Germany); Ulrich Schramm, Thomas E. Cowan, Arie Irman, Karl Zeil, Dominik Kraus, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

Simulations of laser matter interaction at extreme intensities that have predictive power are nowadays in reach when considering codes that make optimum use of high performance compute architectures. Nevertheless, this is mostly true for very specific settings where model parameters are very well known from experiment and the underlying plasma dynamics is governed by Maxwell's equations solely. When including atomic effects, prepulse influences, radiation reaction and other physical phenomena things look different. Not only is it harder to evaluate the sensitivity of the simulation result on the variation of the various model parameters but numerical models are less well tested and their combination can lead to subtle side effects that influence the simulation outcome.

We propose to make optimum use of future compute hardware to compute statistical and systematic errors rather than just find the mots optimum set of parameters fitting an experiment. This requires to include experimental uncertainties which is a challenge to current state of the art techniques. Moreover, it demands better comparison to experiments as inclusion of simulating the diagnostic's response becomes important.

We strongly advocate the use of open standards for finding interoperability between codes for comparison studies, building complete tool chains for simulating laser matter experiments from start to end.

10241-9, Session 2

Electron-positron pair production from electron-laser scattering, the effect of the long pulse

Marija Vranic, Ondrej Klimo, Georg Korn, Stefan Weber, ELI beamlines, Fyzikální ústav AV ?R, v. v. i. (Czech Republic)

A new generation laser system at ELI beamlines will provide a 10 PW peak power in a 150 fs laser pulse. This opens new possibilities for experiments on laser-electron scattering at extreme intensities. High energy photons (x-rays or gamma-rays) are produced through nonlinear Compton scattering, and they subsequently decay into electron-positron pairs. The pair yield depends on several factors: the electron beam energy, the laser intensity and the duration of the interaction. Prevous studies focused mostly on the short lasers (~ 30 fs). However, using a longer laser pulse (~ 150 fs) can be an advantage, because it increases the effective interaction time and can deliver a higher number of pairs. A powerful tool that supports theoretical studies of laser-matter interactions and helps design of experiments are particle-in-cell (PIC) codes. PIC code OSIRIS has an additional Quantum electrodynamics (QED) module that includes discrete photon emission (non-linear Compton scattering) and Breit-Wheeler electron-positron pair production, as well as macroparticle merging that allows to control the total number of particles in the simulation. In this work, OSIRIS is deployed to model the interaction of short and long lasers of extreme intensities (I>10^22) with electron beams obtained from a laser wakefield accelerator. Measurable experimental signatures are discussed, the number of electron-positron pairs and the overall quality of the newly produced beam.

10241-10, Session 2

Electrons in strong electromagnetic fields: spin effects and radiation reaction

Heiko Bauke, Meng Wen, Christoph H. Keitel, Max-Planck-Institut für Kernphysik (Germany)

Various different classical models of electrons including their spin degree of freedom are commonly applied to describe the coupled dynamics of relativistic electron motion and spin precession in strong electromagnetic fields. The spin dynamics is usually governed by the Thomas-Bargmann-Michel-Telegdi equation [1, 2] in these models, while the electron's orbital motion follows the (modified) Lorentz force and a spin-dependent Stern-Gerlach force. Various classical models can lead to different or even contradicting predictions how the spin degree of freedom modifies the electron's orbital motion when the electron moves in strong electromagnetic fields. This discrepancy is rooted in the model-specific energy dependency of the spin induced relativistic Stern-Gerlach force acting on the electron. The Frenkel model [3, 4] and the classical Foldy-Wouthuysen model 5 are compared exemplarily against each other and against the quantum mechanical Dirac equation in order to identify parameter regimes where these classical models make different predictions [6, 7].

Our theoretical results allow for experimental tests of these models. In the setup of the longitudinal Stern-Gerlach effect, the Frenkel model and classical Foldy-Wouthuysen model lead in the relativistic limit to qualitatively different spin effects on the electron trajectory. Furthermore, it is demonstrated that in tightly focused beams in the near infrared the effect of the Stern-Gerlach force of the Frenkel model becomes sufficiently large to be potentially detectable in an experiment. Among the classical spin models, the Frenkel model is certainly prominent for its long history and its wide application. Our results, however, suggest that the classical Foldy-Wouthuysen model is superior as it is qualitatively in better agreement with the quantum mechanical Dirac equation.

In ultra strong laser setups at parameter regimes where effects of the Stern-Gerlach force become relevant also radiation reaction effects are expected to set in. We incorporate radiation reaction classically via the Landau-Lifshitz equation and demonstrate that although radiation reaction effects can have a significant effect on the electron trajectory, the Frenkel model and the classical Foldy-Wouthuysen model remain distinguishable also if radiation reaction effects are taken into account.

Our calculations are also suitable to verify the Landau-Lifshitz equation for the radiation reaction of electrons and other spin one-half particles.

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10241-11, Session 3

Key physical concepts for laser plasma accelerators *(Invited Paper)*

Victor Malka, Ecole Nationale Supérieure de Techniques Avancées (France)

No Abstract Available

10241-12, Session 3

Design and development of the HELL User Station for multidisciplinary experiments

Gabriele Maria Grittani, ELI Beamlines (Czech Republic); Tadzio Levato, Georg Korn, ELI Beamlines, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

HELL is the high energy electron beamline under development at ELIBeamlines, which is expected to produce GeV electrons at high repetition rate. The aim of HELL is dual: to improve the performances of the laser electron accelerator, and to deliver stable beams for external users. In this work, we present the recent developments towards the delivery of stable and calibrated beams for external users. The design of the HELL User Station will be presented and discussed along with simulations and experimental data collected in different facilities.

10241-13, Session 3

Scaling of proton-boron nuclear fusion rate using high power lasers and advanced targets

Lorenzo Giuffrida, Daniele Margarone, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Antonino Picciotto, Fondazione Bruno Kessler (Italy); Andriy Velyhan, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Valentina Scuderi, Pablo G. Cirrone, Istituto Nazionale di Fisica Nucleare (Italy); Josef Krasa, The Institute of Physics (Czech Republic); Jan Dostal, Jiří Ullschmied, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic); Yasunobu Arikawa, Akifumi Yogo, Osaka Univ. (Japan); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

High alpha particle number (~109/sr per shot) has been produced from the p-11B neutron-less nuclear fusion reaction by using different nanosecond-class laser systems at similar intensity (3?1016??/????2) and specially designed B-doped and H-enriched silicon targets. Various experimental campaigns have been recently performed at PALS laser facility in Prague [1 and 2] and are here compared with new experimental results achieved in similar conditions at the GEKKO XII laser facility in Osaka.

CR39 nuclear track detectors at different angles, Time Of Flight (TOF) diagnostics and a Thomson Parabola (TP) spectrometer were used to characterize alpha particle spectra and the angular distributions using different energies of the two laser systems (up to 600 J at PALS and up to 7 kJ at GEKKO XII).

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10241-14, Session 3

Ultra-stable pointing experiments in LWFA and expected performance in the HELL project

Tadzio Levato, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Marcin Rosinski, Institute of Plasma Physics and Laser Microfusion (Poland); Gabriele Maria Grittani, ELI Beamlines (Czech Republic); Michal Nevrkla, Czech Technical Univ. in Prague (Czech Republic); Carlo Maria Lazzarini, Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

The high-energy electron platform in ELI-Beamlines allow the use of different setup configurations for LWFA experiments. The importance of the electron beam stability in term of pointing is critical when the bunch have to be transported or used in combination with a second laser pulse. Here we report on last measurements about the electron pointing stability and discuss the prospective to reach the laser pointing stability level.

10241-15, Session 3

First Draco-PW particle acceleration results *(Invited Paper)*

Ulrich Schramm, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

No Abstract Available

10241-16, Session 4

Starting up European XFEL *(Invited Paper)*

Thomas Tschentscher, European XFEL GmbH (Germany)

No Abstract Available

10241-17, Session 4

ELI-Beamlines: next-generation short-pulse laser systems *(Invited Paper)*

Bedrich Rus, ELI Beamlines (Czech Republic)

No Abstract Available

10241-18, Session 4

10 PW commissioning experiments plans at ELI-NP *(Invited Paper)*

Dan Stutman, Extreme Light Infrastructure-Nuclear Physics (Romania)

No Abstract Available

10241-20, Session 4

Status update of multi-kilojoule, multi-petawatt laser LFEX *(Invited Paper)*

Junji Kawanaka, Osaka Univ. (Japan)

No Abstract Available

10241-21, Session 5

Progress on the 10PW laser project SULF at Shanghai *(Invited Paper)*

Xiaoyan Liang, Shanghai Institute of Optics and Fine Mechanics (China)

No Abstract Available

10241-22, Session 5

High contrast high intensity petawatt J-KAREN-P laser facility at QST *(Invited Paper)*

Mamiko Nishiuchi, Hiromitsu Kiriyama, Alexander S. Pirozhkov, Hironao Sakaki, Yuji Fukuda, Japan Atomic Energy Agency (Japan); Nicholas P. Dover, Imperial College London (United Kingdom); Keniji Nishitani, Nagoya Univ. (Japan); Tsuneaki Miyahara, Kansai Photon Science Institute (Japan); Akito Sagisaka, Japan Atomic Energy Agency (Japan); M. A. Alkhimova, Joint Institute for High Temperatures (Russian Federation); Tatiana A. Pikuz, Anatoly Ya. Faenov, Koichi Ogura, Timur Zh. Esirkepov, Japan Atomic Energy Agency (Japan); Keisuke Kondo, Japan Aerospace Exploration Agency (Japan); Yousuke Watanabe, Kyushu Univ. (Japan); James K. Koga, Sergei V. Bulanov, Masaki Kando, Kiminori Kondo, Japan Atomic Energy Agency (Japan)

We report on the J-KAREN-P laser facility at QST which can provide PW peak power at 0.1 Hz onto target. The system can deliver short pulses with the energy of 30 J, pulse duration of 30 fs after the compression with the contrast level of better than 1012.

Such performance in high field science will give rise to the birth of new applications and breakthroughs, which include relativistic particle acceleration, bright x-ray source generation, and nuclear activation.

The current achieved laser intensity on target is up to >9x1021 Wcm-2 with an energy of ~9 J on target.

The interaction with a 3 to 5-µm Stainless steel tape target provides us electrons having a typical temperature of more than 10 MeV and energetic proton beams with typical maximum energies of > 40 MeV with good reproducibility by the Target Normal Sheath Acceleration regime, which is suitable for many applications including as an injector for medical use, which is one of our objectives.

10241-23, Session 5

Models and simulations of capillary discharges *(Invited Paper)*

Vladimir Gasilov, M. V. Keldysh Institute of Applied Mathematics (Russian Federation); Pavel V. Sasorov, M. V. Keldysh Institute of Applied Mathematics (Russian Federation); Gennadiy Bagdasarov, M. V. Keldysh Institute of Applied Mathematics (Russian Federation); Danila Khikhlukha, ELI Beamlines (Czech Republic)

Capillary discharges have a relatively simple nature. The current pulse creates inside a thin and long capillary channel rather “quiet” plasma temperature and density of which can be controlled and varied within a fairly wide range. Due to these properties, capillary discharges have become a convenient tool for many applications, such as compact particle accelerators, compact X-ray lasers, etc. At first we discuss capillary plasma models used for analytical and numerical analysis of these experiments.

Experimental setup able to accelerate electrons through capillary plasma up to very high energy is a matter of modern research projects like BELLA (LBNL, USA), ELI Beamlines (ELI, Czech Republic) and others. The plasma forms a channel able to guide the laser light, which in its turn forms a plasma wake wave that accelerates the injected electrons. Recent experiments (BELLA, 2013) provide reliable evidences of the possibility to accelerate electrons up to 10 GeV level at a one meter distance.

To achieve a good coupling of a laser pulse with the capillary waveguide it is necessary to have a tool for the simulation of a 3D electron distribution inside the capillary, near its entrance/exit openings as well as near the supply channels which serve for filling a capillary with a neutral hydrogen.

In the second part of the talk we discuss physical as well as numerical capillary discharge models that we use now and also perspective models that we are going to develop. We use the MARPLE3D code (KIAM RAS, 2012) to perform simulations of capillary plasmas. MARPLE3D is a numerical tool designed for simulations of radiative-MHD problems related to experiments with magnetically driven high energy density plasmas.

Our main results are obtained via numerical investigations of several important 2D and 3D effects like those arising at the capillary inlets/outlets.

We also present some results of PIC simulations aimed to study the effect of inhomogeneous plasma at the capillary inlet on the electron dynamics during the early stage of LWFA process.

10241-24, Session 5

Generation and characterization of laser matter interaction at intensity 1022 W/cm2

Deepak Kumar, ELI Beamlines (Czech Republic)

There has been a consistent push to achieve focused laser intensities of 1022-23 W/cm2. Under these conditions many novel processes like radiation reaction, electron-positron pair creation, dominance of radiation pressure over the thermal pressure of plasma and even relativistic ion motion will be dominant. Intensities of > 1022 W/cm2 on current generation PW class lasers can be achieved by tight focusing a beam using an ellipsoidal plasma mirror (EPM). The first part of this presentation will show the results from characterizing the focal spot from such EPMs on a test bench using a CW laser.

Laser-solid interaction experiments at such high intensities are expected to yield copious amounts of gamma rays in the multi MeV range. Thus we are developing dedicated gamma ray diagnostics for such experiments. The second part of this presentation will present results from a recent absolute calibration and test of a forward Compton scattering spectrometer at a bremsstrahlung beamline. The spectrometer covered an energy range from 4-20 MeV with a resolution of about 2 MeV. The measured dynamic range was approximately 30:1.

10241-25, Session 6

Progress toward rep-rated multi-PW lasers *(Invited Paper)*

Todd Ditmire, National Energetics (United States)

No Abstract Available

10241-26, Session 6

Development of high-energy kW-class picosecond thin-disk laser systems *(Invited Paper)*

Thomas Nubbemeyer, Ludwig-Maximilians-Univ. München (Germany)

No Abstract Available

10241-27, Session 6

New advanced characterization tools for PW-class lasers

Fabien Quéré, Commissariat à l'Énergie Atomique (France)

Spatio-temporal couplings (STC) of laser beams are ubiquitous in ultrafast optics. In the femtosecond range, chirped-pulse amplification (CPA), the key technology of amplified ultrashort pulses, relies on the use of massive STCs induced at different locations in laser systems (for instance by gratings or prisms), which should all eventually perfectly cancel out at the laser output. Residual STCs, for example resulting from imperfect compensation, decrease the peak intensity at focus by increasing both the focal spot size and the pulse duration. This is particularly detrimental for ultrahigh-intensity (UHI) lasers, which aim for the highest possible peak intensities. However, it is precisely with these lasers that such uncontrolled defects are most likely to occur, due to the complexity of these systems and the large diameters of the output beams.

Accurately measuring STCs is thus essential in ultrafast optics. Significant progress has been made in the last decade, and several techniques are now available for the partial or complete spatiotemporal characterization of near-visible femtosecond laser beams. However, none of these has yet been applied to UHI femtosecond lasers, due to the difficulty of handling these large and powerful beams. As a result, all UHI lasers are currently characterized under the unjustified and unverified assumption of the absence of STCs, using separate measurements in space and time.

This situation is now becoming a major bottleneck for the development of UHI lasers and their applications. In particular, the optimal and reliable operation of PW-class lasers now available or under construction all around the world will simply not be possible without a proper spatiotemporal metrology. In this talk, we present the first complete spatiotemporal experimental reconstruction of the field E(t,r) for a 100 TW peak-power laser, obtained using self-referenced spatially-resolved Fourier transform spectroscopy [1,2], and thus reveal the spatiotemporal distortions that can affect such beams [3]. This new measurement capability opens the way to in-depth characterization and optimization of ultra-intense lasers and ultimately to the advanced control of relativistic motion of matter with femtosecond laser beams structured in space–time.

10241-28, Session 6

Technology development for multi-PW CPA and OPCPA-based laser systems

Ian Musgrave, Steve P. Blake, Alexis Boyle, Oleg V. Chekhlov, John L. Collier, STFC Rutherford Appleton Lab. (United Kingdom); R, J. Clark, Science and Technology Facilities Council (United Kingdom); Steve Hancock, Robert Heathcote, Cristina Hernandez-Gomez, Chris J. Hooker, Marco Galimberti, Pavel Matousek, David Neely, Peter A. Norreys, B. T. Parry, Rajeev Paramel Pattathil, Waseem Shaikh, Daniel R. Symes, Y. Tang, Trevor B. Winstone, Brian E. Wyborn, STFC Rutherford Appleton Lab. (United Kingdom)

The Central Laser Facility has made leading contributions to the development of Optical Parametric Chirped Pulse Amplification. Through a series of projects the technique has been developed from pre-amplifiers to feasibility tests at large aperture. The culmination of this work is the proposal for and development of a 10PW upgrade to the current Vulcan laser facility. The new beam line will be fully integrated with the existing 1PW beam line enabling new types of experiments 1PW + 10PW. In addition to the peak power the requirement on the laser pulse will be high contrast, good focusability and able to reach intensities greater than 1023 W cm-2. Whilst funding is being sought to fully deliver this goal a technology development programme for multi-PW OPCPA systems has been established to ensure that the relevant components required are available when funding is identified. Some aspects of the programme are connected directly with the OPCPA technique; others are related to all types of high energy CPA systems. Different subjects have been discussed and a series of eight areas has been identified and some of our work in these areas will be presented:

1. Gratings: the damage threshold of the compression gratings is the bottleneck of CPA laser systems;

2. Highly deuterated KD*P: for large aperture OPCPA the best candidate crystal is currently KD*P, already used in high power fusion lasers. However, the combination of the requirement for high deuteration (>80%), aberrated transmitted wavefronts (~?) and long delivery time (~2 year) demand further research on the availability and the optical quality of crystals;

3. Broadband Mirror: whilst broadband coatings for s-polarized beam capable of managing the bandwidth (>150nm) and the fluence (100mJ/cm2@30fs) are available, research is required to develop coatings for p-polarization and for the final OAP;

4. Deformable Mirror: the required wavefront quality for the 10PW compressor is difficult to be achieved without a deformable mirror (DM);

5. Short Focal Length Parabola: the requirement of high intensity is usually addressed using ever shorter focal lengths. However, for f/#<3 the paraxial approximation starts to fail and for f/#<1 vectorial theory is required;

6. Contrast: the contrast is a key requirement for high power short pulse laser. While ns contrast has been fully understood and there are different ways to manage it, the ps contrast requires more investigation to understand better its origin and how to improve it;

7. Component test lab: it is important to fully test the pump laser technology and each optical component. For that purpose a new laboratory has been setup adjacent to the existing 10PW evaluation frontend with a pump laser capable of delivering 15J in 3ns at 526.5nm;

8. Medium Size OPCPA: while small aperture OPCPA stages are already in use at CLF, the scaling to large aperture (tens of centimetres) requires a different design. Using the component test lab a 38mm aperture OPCPA is under test, investigating KD*P at different deuteration levels.

10241-29, Session 6

Development of high energy, sub-15 fs OPCPA system operating at 1 kHz repetition rate for ELI-Beamlines facility

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The ELI-Beamlines facility in the Czech Republic, currently under construction, will house four state-of-the-art high intensity lasers operating at high repetition rates. We report here the state of the development of the L1 laser based on OPCPA technology pumped by picosecond pulses from high energy thin disk lasers. This system is designed to operate at 1 kHz and to generate sub-15 fs pulses with energies in excess of 100 mJ. After its completion the system will provide users with a stable driver for high quality secondary sources, such as plasma x-ray source, HHG, etc.

Given the requirement for the high average power of the short pulse train, the OPCPA is an ideal solution, as it fundamentally does not suffer from thermal effects and at the same time can support extremely large bandwidth, as well as guarantee high intensity contrast when pumped by picosecond pulses. The pulses from 6fs Ti:sapphire oscillator are stretched to less than 3 ps (FWHM) and amplified in only seven OPCPA stages (BBO and LBO crystals each with a thickness around 2 mm) . The amplified pulses will be compressed with chirped mirrors, while the fine tuning of the dispersion is achieved using an AOPDF.

The first four OPCPA stages operating in air have been completed and the resulting performance provided verification of the overall beamline concept. The achieved broadband pulse energy at 1 kHz is 11 mJ with stability of 3% rms and an excellent beam quality with M2 <1.25. The pulse compression of the picosecond pulse using chirped mirrors has led to generation of 12fs pulses [1]. Due to the high intensity of the of the picosecond pulses in the OPCPA (pump and signal) the last three LBO stages and the final chirped mirror compressor are operated in vacuum.

Several high average power CPA pump lasers based on Yb:YAG thin disk regenerative amplifiers have been developed for this project: 30 mJ/1 kHz, 100 mJ/1 kHz , and 230 mJ /1 kHz, all with excellent beam quality (M2 <1.2) and energy stability (<1% rms). 650 mJ/ 1 kHz thin disk multipass amplifier is also under development. All of the pump lasers are passively synchronized though seed from the common broadband Ti:sapphire oscillator. The seed pulses at 1030 nm for the thin disk amplifiers are stretched in temperature stabilized chirped fiber Brag grating (CFBG) stretchers to sub-ns pulse durations. The pulses from the thin disk amplifiers are compressed to 3 ps (FWHM) using MLD grating compressors and converted to SHG (515 nm) in LBO crystals, where the last three pump lasers for the OPCPA stages 5,6 and 7 have compressors and SHG operation under vacuum. High stability of the OPCPA, as demonstrated on the stages 1-4, is supported by active temporal stabilization of the pump relative to the broadband signal pulses to 15 fs rms.

The reliability of such complex laser system must be supported by a sophisticated control system. The control system being developed in Labview and EPICS has in excess of 1000 control points, (including 60 cameras, 88 motors, 60 energy meters). The main functionality of the control system is in fast response (<1 ms) machine safety system, event based electronic timing system, as well as monitoring of laser and environmental parameters.

10241-30, Session 7

Modelling the effect of radiation reaction on the absorption of ultra-intense laser pulses in overdense targets

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Future multi-petawatt laser facilities will allow the experimental study of plasma interactions with ultra-high intensity laser pulses. The peak intensities of such systems will exceed 10^23 Wcm^-2, subjecting the plasma dynamics to strong field physics effects. Of particular interest is radiation reaction, a process by which a radiating electron experiences a recoil force due to photon emission. Radiation reaction not only affects the dynamics of the radiating electrons, it also indirectly impacts ions through modification of the self-consistent electromagnetic fields within the plasma. Specifically, it has been demonstrated that classical radiation reaction causes a decrease in the ion energy obtained from thick targets in the hole-boring regime [1].

We consider the interaction of an ultra-intense (2x10^23 Wcm^-2, 60 fs FWHM duration) Gaussian pulse with solid-density aluminium targets between 200-500 nm in thickness. The areal density of the targets is sufficiently high that the electrostatic pressure exceeds the radiation pressure of the laser and ion acceleration occurs in the hole-boring regime. We have shown in an initial numerical investigation of the plasma dynamics in this interaction regime, that radiation reaction plays a small but non-negligible role. Due to the small role of radiation reaction in this regime, non-linear QED effects can be neglected. Whilst previous work has described the absorption of a relativistic laser pulse into overdense targets [2,3,4], we also incorporated the effects of the radiation reaction force through a perturbative approach. A particular outcome of this approach is an estimate of the reflection coefficient of laser light from the target, taking into account the radiation reaction force. This allows the piston velocity and the conversion efficiency of the laser energy to different plasma species to be deduced. These estimates are supported by 1D numerical simulations using a QED-particle-in-cell code [5]. This study is of benefit to the laser-plasma community as it will lead to a better understanding of the process of relativistic induced transparency. The effects predicted by this model may be tested experimentally in future multi-petawatt laser facilities.

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10241-31, Session 7

Study of L4 nanosecond pedestal effect on pre-plasma using nonlocal hydrodynamic simulations and consequences for high-field interaction

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L4 beamline, the future most intense laser on the world, will allow to achieve new regimes of extreme laser-matter interaction reaching the intensities of 10^24 W/cm^2. Even the excellent contrast of 10^11 of the laser pulse provided by the cutting edge optical components will lead to a significant pre-plasma creation which can affect or eventually suppress the interaction effect when the main pulse arrives. Hydrodynamic simulation is the most appropriate tool to address the effect of plasma creation due to such a pre-pulse lasting several nano-seconds. Nevertheless, it is well known that the commonly used diffusion model of the transport of electrons leads to the heat flux overestimation and the strategy of applying the flux limiter lacks a solid physical background. Our developed nonlocal transport hydrodynamic extension model brings an important improvement to the energy transport in hydrodynamics including radiation and electron transport in a consistent way, where any flux limitation need not to be used.

An extensive set of simulation of different Z solid targets irradiated by the L4 pre-pulse aim to describe the profile and scale length of the created pre-plasma in a detailed way. It also addresses the dominant physical phenomena with respect to the material, mean pulse intensity, and time evolution, where the main focus is a detailed understanding of the region around the critical density. Finally, the pre-plasma modeled by the nonlocal transport hydrodynamic extension is used in particle-in-cell simulations as initial condition to quantify its effect on high-field laser-plasma interaction.

10241-32, Session 7

3D simulation in the lambda-cube regime of the petawatt-class laser with plasma slab

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No Abstract Available

10241-33, Session 7

Evolution of relativistic electron vortices in laser plasmas

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The interaction of high intensity laser radiation with underdense plasma may lead to the formation of electron vortices. Though being quasistationary on an electron timescales, these structures tend to expand on a proton timescale due to Coloumb repulsion of ions. Using a simple analytical model of a stationary vortex as initial condition, 2D PIC simulations are performed. A number of effects are observed such as vortex boundary field intensification, multistream instabilities at the vortex boundary, and bending of the vortex boundary with the subsequent transformation into smaller electron vortices.

The talk will be based on the following paper: Phys. Plasmas, 23, 093116 (2016) and further research including the evolution of binary vortex systems

10241-34, Session 7

Gamma beams generation with high-intensity lasers for the study of two photon Breit-Wheeler pair production

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Direct production of electron-positron pairs in photon collisions is one of the basic processes in the Universe. The linear Breit-Wheeler (BW) pair creation process (?+? to e++e-), is the lowest threshold process in photon-photon interaction, controlling the energy release in Gamma Ray Bursts and Active Galactic Nuclei [1]. It is also responsible for the TeV cutoff in the photon energy spectrum of extra-galactic sources. The linear BW process has never been clearly observed in laboratory with important probability of matter creation [2]. Using MeV photon sources a new experimental set-up based on numerical simulations with QED effects is proposed. This scheme offers a possibility of conducting a multi-shot experiment with a reliable statistics on laser systems with pulse energies on the level of a few joules to tens of joules, and in a low noise environment without heavy elements. This scheme relies on a collision of relatively low energy (few MeV), intense photon beams. Such beams can be created in the interaction of intense laser pulses with thin plastic targets or dense gas jets. By colliding two of them in vacuum, one would be able to produce a significant number of electron-positron pairs in a controllable way.

We provide details of the experimental setup, analytical estimates and an optimization study using numerical simulations with QED effects of the expected yield of reactions for different possible ways of creation of the MeV photon source. Using MeV photon sources [3] obtained in numerical simulations at ultra high intensities in the synchrotron-like radiation dominated regime more than 10^4 BW pairs per shot can be achieved [4]. A comparison of these results with Bremsstrahlung sources obtained with numerical simulations will be presented. When two of these gamma beams collide at particular angles, our analytical calculations demonstrate a beaming effect which generates beams of pairs that can be more easily detected in the laboratory [5]. This beaming effect has been confirmed in photon collision simulations using a recently developed innovative algorithm [6] that allows us to propose robust experimental designs. Moreover, the noise level due to other pair creation processes is estimated. The preparation of first experiments on the ECLIPSE facility at CELIA, to prepare gamma and pair diagnostics, and on the APOLLON facility at the Université Paris-Saclay, to optimize pair generation, will be presented.

The possibility to study this process in the laboratory would allow to test new concepts of pair plasma production and to explore this pair creation process in the ultra high field regime with important potential applications in astrophysics. Moreover, the obtained optimized gamma sources could also have promising applications as radiography sources.

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10241-35, Session 7

A kinetic model for the high energy synchrotron radiation in ultra-strong laser-matter interactions

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The spectacular development of new laser facilities with expected peak intensity exceeding 10^23W/cm^2 is attracting more and more interest for new regimes occurring at ultra-high laser intensities, which will be accessible by experiment in the near future [1]. Such regimes involve ultra-strong electromagnetic fields, where the collective effects and the radiation reaction are of great importance and tend to strongly impact the plasma dynamics [2]. In particular, the ions can no longer be considered as "background plasma particles" since the quiver electron energy can be comparable with the ion rest mass. It has been recently demonstrated that the ion mass affects the high energy synchrotron-like radiation and laser energy absorption [3]. Here, we present a kinetic model which accounts for both the ion mass and the laser spot size on the high energy synchrotron-like radiation emitted by ultra-relativistic electrons. The influence of the ion mass and the laser spot size on the process of relativistic self-induced transparency is also discussed and related to the proprieties of the synchrotron radiation (angular distribution, energy spectrum). To verify our analytical predictions, we have considered the interaction of an ultra-intense laser pulse (I= 10^23 W/cm^2 and ?= 40fs) with an overdense thin plasma. 2D numerical simulations have been performed with a QED-particle-in-cell code [4], by considering three plasmas (Hydrogen, Deuterium, Tritium) as well as three laser spot sizes (3 ?m, 6 ?m and 15 ?m). The characteristics of the high energy synchrotron radiation (in particular those related to ion mass) could be detected and measured on future laser facilities.

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10241-36, Session 7

Emission of ? rays in laser-solid interactions

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Advances in laser technology with multi-petawatt lasers producing short pulses which, when focused to a spot on the order of a few microns, produce electromagnetic fields of intensities I ?? 1022 W/cm2 opened new possibilities in generating ? rays in laboratory by various processes involving fast electrons which are generated during the interaction of an intense laser pulse with a target. Two main sources of energetic photons generated in an interaction with a low-Z thin foil target are Bremsstrahlung and radiation reaction (including non-linear Compton scattering).

These processes are investigated in the high intensity regime of laser plasma interaction (I ~ 1021 – 1023 W/cm2) by using a combination of Particle-in-Cell simulations with the code EPOCH, which include radiation reaction and photon generation, and Monte Carlo radiation transport simulations with the code PENELOPE. The relative importance/ contribution of the various processes is analyzed as function of the laser-matter interaction parameters. The investigation concentrates on the influence of target thickness, preplasma conditions, and surface structure on the angular and energy distribution of ? photons with energies E > 1 MeV. It aims to distinguish signatures of ? photons generated by the nonlinear inverse Compton scattering versus those generated by Bremsstrahlung. It is demonstrated that the presence of a microstructure, or preplasma at the front side of the target may lead to a significant increase in the amount of emitted ? photons. Depending on the interaction parameters, the angular distribution of the ? photons ranges from one with some prominent directions to an almost isotropic one for long preplasma profiles combined with higher driving pulse intensities. In the regimes with the presence of prominent directions, we show that the angular distribution of emitted ? photons depends on the geometry of the front side of the foil - either pre-formed, or formed, owing to the plasma dynamics, by the driving pulse during the interaction.

10241-37, Session 7

Particle dynamics and pair production in tightly focused standing wave

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With the advent of 10 PW laser facilities, new regimes of laser-matter interaction are opening since effects of quantum electrodynamics, such as electron-positron pair production and cascade development, start to be important. The dynamics of light charged particles, such as electrons and positrons, is affected by the radiation reaction force. This effect can strongly influence the interaction of intense laser pulses with matter since it lowers the energy of emitting particles and transforms their energy to the gamma radiation. Consequently, electron-positron pairs can be generated via Breit-Wheeler process. To study this new regime of interaction, numerical simulations are required. With their help it is possible to predict and study quantum effects which may occur in future experiments at modern laser facilities.

In this work we present results of electron interaction with an intense standing wave formed by two colliding laser pulses. Due to the necessity to achieve ultra intense laser field, the laser beam has to be focused to a ~?m-diameter spot. Since the paraxial approximation is not valid for tight focusing, the appropriate model describing the tightly focused laser beam has to be employed. In tightly focused laser beam the longitudinal component of the electromagnetic field becomes significant and together with the ponderomotive force they affect the dynamics of interacting electrons and also newly generated Breit-Wheeler electron-positron pairs. Using the Particle-In-Cell code we study electron dynamics, gamma radiation and pair production in such a configuration for circular and linear polarization and different types of targets.

10241-38, Session 7

On an impact of radiation reaction on plasma waves induced by ultra-intense laser pulse

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One of the most promising possible applications of such new powerful laser facilities as ELI Beamlines is particle acceleration by longitudinal electric fields generated by nonlinear propagation of intense laser pulses through plasma (LWFA scheme [1,2]). However, since for modern facilities Lorentz factor of electron quiver oscillations in such a huge electromagnetic field becomes already of the order of hundreds, radiation reaction effects should also come into play.

As is well known, both longitudinal and transverse modes are capable for propagation through a cold plasma [3] and in linear regime are independent. In nonlinear (relativistic) regime, linearly polarized transverse modes become unstable with respect to conversion to longitudinal waves, whereas circularly polarized transverse waves still remain stable. A new effect due to radiation reaction is that circularly polarized waves become unstable as well, thus being also partially converted to the longitudinal ones. This effect arises due to radiation reaction entirely, in ultrarelativistic regime competes with the usually employed ponderomotive mechanism and in principle could be implemented for particle acceleration.

Here we investigate an impact of radiation reaction on propagation of a high intensity electromagnetic pulse through a cold plasma. We provide both numerical simulations and a one-dimensional analytical model, which can be used to optimize the conditions for electron acceleration in a regime when radiation reaction becomes essential.

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10241-39, Session 7

Initiation of self-sustained QED cascades in generic electromagnetic field of electric type

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Generation of self-sustained (or A-type, [1]) QED cascades is one of intriguing QED phenomena that are anticipated to become observable under laboratory conditions during the next decade due to awaited forthcoming ultra-high intensity laser facilities. Possibility of initiation of such cascades strongly depends on both field strength and structure, and is quantified by the value of so called quantum dynamical parameter chi of particles involved in laser driven dynamics (see e.g. [2] for details). This parameter can be interpreted as a local field strength in units of Sauter-Schwinger field E_S in the proper reference frame of an electron. Thus if initially slow seeding particles with $chill 1$ start accelerating in laser field so violently that chi grows up to $sim 1$ during time interval shorter than laser period then A-type cascade can occur.

We present a general expression for time dependence of the key parameter chi for a seed electron in a slowly varying strong ($a_0gg 1$) electromagnetic field of electric ($E^2-H^2>0$) type on a time scale $1/a_0omega ll t ll 1/omega$. We show that at this time scale chi is always growing as time squared while the coefficient is determined by a local field configuration. Our result generalizes a few known expressions of this sort for various particular field models, e.g. the rotating electric field [2], circularly or linearly polarized standing waves [3] and multiple focused beams [4]. The obtained general expression for $chi(t)$ allows to generalize the condition of QED cascade initiation that was originally conjectured in [2].

In Ref. [4] it was proposed that in order to maximize cascade multiplicity for a given laser power one should search for field configurations that maximize growth rate of chi. In context of that idea our general expression can be useful in further searches for optimized field configurations favorable to design future experiments by reducing such critical requirements as e.g. the net laser power.

It has been implicitly accepted in the literature that experimental schemes for initiation of seeded QED cascades should involve at least a couple of laser pulses. Using our new formula we show that cascade can be generated even by a single focused laser pulse. Even though such a setup would certainly require higher total intensity, it nevertheless provides certain advantages and is crucial for debates on maximal intensity attainable with high power lasers [2].

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10241-40, Session 8

Extreme laser pulses for possible development of boron fusion power reactors for clean and lasting energy

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Fusion energy from protons reacting with 11B was known to be very difficult and impossible for energy generation, though highly desired because of negligible radioactivity. A radical change appeared by using of sub-picosecond laser pulses of extreme >Petawatt power if instead of thermal laser-plasma interaction, the non-thermal transfer of laser energy into ultrahigh accelerated macroscopic plasma blocks produced the ignition of fusion. Then the fusion reaction of boron was easy [1]. Further progress needed the measured ultrahigh magnetic field trapping and finally the experimental confirmation of the expected avalanche multiplication at boron fusion [2][3][4]. The basic design of a reactor [3][5] is further elaborated. An essential advantage is that the ignition using ultrafast plasma block acceleration by the extreme laser pulses results in a direct drive ignition in contrast to the usual indirect drive in laser fusion with all its complications. Further questions for the design of the reactor are discussed. The principle of nonlinearity according to Feynman (see Chapter 6.3 of [5]) is related to results of Silva [6].

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10241-41, Session 8

Attosecond gamma-ray pulses and angle-resolved-stochastic photon emission in the quantum-radiation-dominated regime

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We demonstrate the feasibility of generation of bright ultrashort gamma-ray pulses and the signatures of stochastic photon emission via the interaction of a relativistic electron bunch with a counterpropagating tightly-focused superstrong laser beam in the quantum-radiation-dominated regime. We consider the electron-laser interaction at near-reflection conditions when pronounced high-energy gamma-ray bursts arise in the backward-emission direction with respect to the initial motion of the electrons. The Compton scattering spectra of gamma-radiation are investigated using a semiclassical description for the electron dynamics in the laser field and a quantum electrodynamical description for the photon emission. We demonstrate the feasibility of ultrashort gamma-ray bursts of hundreds of attoseconds and of dozens of megaelectronvolt photon energies in the near-backwards direction of the initial electron motion. The tightly focused laser field structure and radiation reaction are shown to be responsible for such short gamma-ray bursts, which are independent of the durations of the electron bunch and of the laser pulse. Moreover, the quantum stochastic nature of the gamma-photon emission is exhibited in the angular distributions of the radiation and explained in an intuitive picture. Although, the visibility of the stochasticity signatures depends on the laser and electron beam parameters, the signatures are of a qualitative nature and robust. The stochasticity, a fundamental quantum property of photon emission, should thus be measurable rather straightforwardly with laser technology available in near future.

10241-42, Session 8

Tertiary particle physics with ELI: from challenge to chance

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nteraction of high-intensity laser pulses with solid state targets results in generation of intense pulses of secondary particles via electromagnetic interaction : electrons, ions, hard x-rays. The beams of these particles can be used to produce various types of third-generation particles, beyond electromagnetic also other types of fundamental interactions can be involved in this process [1]. As the most interesting tertiary particles could be mentioned positrons, neutron, muons. This paper shall extend our previous analysis of this topic [2]: it discusses selected technical problems of design and realization of applicable sources of these particles and presents some more elaborated proposals for potential meaningful / hopefuly realistic exploitations of this technology.

(1)Tertiary Sources (TS) : First Development Steps. This part of the presentation includes the topics as follows: (11) Pulsed positron sources: Verified solutions of laser-driven positron sources [3] [4] [5], development towards applicable facilities. Some unconventional concepts of application of lasers for positron production [6]. Techniques for realization of low/very-low energy positrons. (12) Taylored neutron sources [7]: Neutron sources with demanded space distribution, strongly beamed and isotropic solutions [8] [9]. Neutron generation with taylored energy distribution. Problem of the direct production of neutrons with very low energy [10] [11]. (13) Potential muon sources: Proof-of-principle laser experiment on electron / photon driven muon production [12] [13]. Study of the possibility of effective generation of surface muons. Problems of the production of muons with very low energy.

(2) Fundamental & Applied Physics with TS: This part of the talk presents the themes: (21) Diagnostic potential of TS: Lepton emission as a signature of processes in extreme systems. Passive and active diagnostics using positrons, problems of detection and evaluation. Potential diagnostic applications of muons. Concrete application study: muon tomography. (22) Antilepton gravity studies [14]: Possibility of antimattter gravity research using positronium and muonium [15] [16]. Lepton / antilepton gravity studiesactive with relativistic particle beams [17]. First-phase practical application : positron production for filling (commertial) particle traps, development base for multiple microtrap systems. (23) Hidden world searching [18] : Potential laser-based production / detection of selected dark mattter particles - axions, hidden photons [19] [20]. Search for hidden particles in nuclear decay processes [21]. Potential application output: intense positronium source.

Conclusion: The extensive feasibility study confirms the potential of ELI to contribute to the solution of Grand Challenge Problems of physics. Laser-produced tertiary particles will play important role in this effort.

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10241-43, Session 9

High-energy quantum processes in extremely intense laser pulses *(Invited Paper)*

Christoph H. Keitel, Max-Planck-Institut für Kernphysik (Germany)

No Abstract Available

10241-44, Session 9

Aspects of QED in laser-matter interactions *(Invited Paper)*

Mattias Marklund, Umeå Univ. (Sweden)

Both current and future high-intensity laser facilities are and will be capable of delivering intensities that accelerate particles to relativistic speeds, as well as provoking matter to display some of its quantum electrodynamical (QED) properties. Effects such as discrete photon emission and pair production via bremsstrahlung in high-Z target are examples of such processes. Taking the experimental capabilities even further, the possibilities to probe, e.g., vacuum birefringence and related effects have been extensively discussed in the literature. For this prospects to be properly understood and predicted, development of both analytical and numerical tools is necessary. Examples of such developments are the treatment of the laser field as a background field when there is a significant energy repartitioning between fields, photons, and particles, or of QED driven cascades, where a large number of particles of particles are created during a short time, requiring new numerical methods for handling the particle growth. Here I will briefly describe some of the challenges in this field, how we can find signatures of QED physics, and how this may also tie in to other fields of research.

10241-45, Session 9

QED cascades and vacuum birefringence with new PW-class lasers *(Invited Paper)*

Thomas Grismayer, Instituto Superior Técnico (Portugal)

No Abstract Available

10241-46, Session 9

Plasma physics and ultra-high intensity interaction at ELI-Beamlines *(Invited Paper)*

Stefan A. Weber, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

The forthcoming ELI-Beamlines (ELI-BL) 10 PW laser L4 will span fundamental research topics from high-field physics to new extreme states of matter such as radiation-dominated, high-pressure quantum, warm dense matter and relativistic plasmas. The L4 laser is a unique tool due to its relatively long pulse-length of 150 fs. Also discussed are future possibilities to create laser pulses, which go beyond the present 10 PW level. Plasma-based photonic devices for amplifying, focusing and manipulating light as well as enhanced selfphase modulation techniques would allow much higher power levels than can be handled with present-day technology.

In this talk an overview is given of the technological infrastructure P3 (Plasma Physics Platform) as well as the envisaged laser configuration and of the theory and simulation activities of relevance to the first high-field experiments foreseen in ELI-BL. Emphasis is on simulation of realistic configurations of relevance to actual experiments.

10241-47, Session 9

New frontiers in numerical modeling of PW laser plasma interaction

Ricardo A. Fonseca, Instituto Superior Técnico (Portugal)

No Abstract Available

10241-48, Session 10

Ion acceleration experiments employing PW-class systems *(Invited Paper)*

Marco Borghesi, Queen's Univ. Belfast (United Kingdom)

No Abstract Available

10241-49, Session 10

Radiation reaction revisited *(Invited Paper)*

Hartmut Ruhl, Ludwig-Maximilians-Univ. München (Germany)

Starting from first principles the physics of radiation reaction for strong laser fields interacting with electrons and positrons is revisited. With the help of a Wigner formulation of QED a derivation of a system of molecular dynamical (MD) equations of motion with a new radiation reaction term and spin is given. The new equations obtained are delay equations which promise to be void of the problems encountered with the LAD theory.

10241-50, Session 10

Controlled acceleration of cryogenic layered deuterium ion beams *(Invited Paper)*

David Neely, STFC Rutherford Appleton Lab. (United Kingdom)

No Abstract Available

10241-51, Session 10

Plasma formation in noncircular capillary discharges

Gennadiy Bagdasarov, Pavel Sasorov, Alexey Boldarev, Olga Olkhovskaya, Vladimir Gasilov, M. V. Keldysh Institute of Applied Mathematics, RAS (Russian Federation); Danila Khikhlukha, ELI Beamlines (Czech Republic); Daniele Margarone, Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Sergey V. Bulanov, National Institutes for Quantum and Radiological Science and Technology (Japan); Stepan S. Bulanov, Carlo Benedetti Jr., Anthony J. Gonsalves, Wim P. Leemans, Lawrence Berkeley National Lab. (United States)

For several decades the capillary discharges have been under intensive investigations due to various promising applications, e.g. for the laser electron accelerators as well as for the X-ray lasers [1,2]. A major portion of the experiments were done with circular cross-section capillaries. An appropriate theoretical and numerical study of circular capillaries can be greatly simplified to a 1D model [3] assuming rotational and axial symmetries of the plasma flow in a long thin channel. On the other hand, studying capillaries with non-circular cross-section [4], which have been attracting substantially less attention, requires more complicated 2D models. Such capillaries, for example, square one, possess several advantages related to their fabrication as well as for plasma diagnostics

The aim of our work is to compare the plasma density and temperature distributions formed at the quasistationary stage of the discharge. We present the results of MHD simulations of hydrogen-filled capillary discharges with circular and rectangular cross-sections under almost the same conditions characterizing the initial configurations and the external electric circuit. The simulation parameters are choosen to correspond to the capillary discharge based waveguide for the laser wakefield accelerator [5].

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10241-52, Session 11

GeV laser-plasma acceleration and betatron radiation *(Invited Paper)*

Nelson C. Lopes, Instituto Superior Técnico (Portugal)

No Abstract Available

10241-53, Session 11

ELIMAIA: laser driven ion beamline for multidisciplinary applications at ELI *(Invited Paper)*

Daniele Margarone, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Giuseppe A. P. Cirrone, Valentina Scuderi, Istituto Nazionale di Fisica Nucleare (Italy); Francesco Schillaci, Istituto Nazionale di Fisica Nucleare (Ireland); Francesco Paolo Romano, Istituto Nazionale di Fisica Nucleare (Italy); Lorenzo Giuffrida, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Giacomo Cuttone, Istituto Nazionale di Fisica Nucleare (Italy); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

The main direction proposed by the community of experts in the field of laser driven ion acceleration is to improve the particle beam features (maximum energy, charge, emittance, divergence, monochromaticity, shot-to-shot stability) in order to demonstrate reliable and compact approaches to be used for multidisciplinary applications, thus, in principle, reducing the overall cost of a laser-based facility compared to a conventional accelerator one.

The mission of the laser driven ion target area at ELI-Beamlines, called ELIMAIA (ELI Multidisciplinary Applications of laser-Ion Acceleration), is to provide stable, fully characterized and tuneable beams of particles accelerated by PW-class lasers, and to offer them to the user community for multidisciplinary applications. The ELIMAIA beamline is currently being designed and developed at the Institute of Physics of the Academy of Science of the Czech Republic (IoP-ASCR) in Prague and at the National Laboratories of Southern Italy of the National Institute for Nuclear Physics (LNS-INFN) in Catania.

An international scientific network particularly interested in future applications of laser driven ions for hadrontherapy, ELIMED (ELI MEDical applications), has been established around the implementation of the ELIMAIA experimental system. The two research groups currently working on the implementation of the ELIMAIA beamline have been performing numerical simulations and experimental tests at international high power laser facilities aimed at the optimization of the laser driven ion source on target as well as the ion beam transport and dosimetric systems. Preliminary results will be presented and discussed.

10241-54, Session 11

Ion acceleration with radiation pressure in quantum electrodynamic regimes *(Invited Paper)*

Dario Del Sorbo, David Blackman, Univ. of York (United Kingdom); Remi Capdessus, Univ. of Strathclyde (United Kingdom); Kristina Small, Cody Slade-Lowther, Christopher P. Ridgers, Univ. of York (United Kingdom)

Ion acceleration using the Hole Boring and Light Sail approach, in the quantum electrodynamic regime, is simulated with a particle-in-cell code (EPOCH), accounting for QED emissions stochastically. Scaling laws are derived.

10241-55, Session 11

Generation of attosecond electron pulses using petawatt lasers

Katarzyna Krajewska, Felipe Cajiao Velez, Jerzy Z. Kaminski, Univ. of Warsaw (Poland)

Ionization of positive ions using relativistically-strong short laser pulses is investigated. This is done by means of the relativistic strong-field approximation [1,2], which is particularly suitable to treat highly energetic ionization. We observe the appearance of broad interference-free patterns in the high-energy portion of the electron spectra, which extend over hundreds of driving photon energies. These structures can be controlled by changing parameters of the driving laser pulse. As we demonstrate, the electrons comprising these broad structures can form attosecond pulses. While we present the fully numerical results, their interpretation is based on the saddle-point approximation of the ionization probability amplitude. The conditions enabling generation of ultrashort electron pulses are also studied.

This work is supported by the National Science Centre (Poland) under Grant No. 2014/15/B/ST2/02203.

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10241-56, Session 11

Ultra-intense laser interaction with specially-designed targets as a source of energetic protons

Jan P?ikal, Martin Matys, Czech Technical Univ. in Prague (Czech Republic); Martina ?áková, ELI Beamlines (Czech Republic); Lorenzo Giuffrida, ELI Beamlines (Czech Republic); Jan Grym, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Jan Pro?ka, Czech Technical Univ. in Prague (Czech Republic); Daniele Margarone, ELI Beamlines (Czech Republic)

The efficiency of laser driven ion acceleration strongly depends on the kind of targets used in the experiment. In the last decade, it was observed in several experiments that specially designed nanostructured solid targets may substantially increase the number and energy of accelerated protons and/or to modify profiles of generated proton beams. In the last year, a thin cryogenic hydrogen solid foil was successfully used in the experiment, high laser-to-proton energy conversion efficiency was demonstrated with ns-class laser and even higher enhancement is theoretically anticipated using PW-class, femtosecond lasers.

In this contribution, we will discuss the optimization of laser driven proton acceleration efficiency by nanostructured targets, interpret the experimental results showing the manipulation of proton beam profiles by nanosctructured rear surface of the targets and investigate the acceleration of protons from hydrogen solid ribbon by PW-class lasers, with the help of multidimensional particle-in-cell simulations. Microstructured hollow targets are proposed to enhance the absorption of the laser pulse energy while keeping the target thickness to minimum, which is both favorable for enhanced efficiency of the acceleration of protons. The fabrication of an ultrathin hollow target (prototype) by focused ion beam milling is also described. Thin targets with grating structures of various configurations on their rear sides stretch the proton beams in the perpendicular direction to the grating orientation due to transverse electric fields generated inside the target grooves and can reduce the proton beam divergence in the parallel direction to the grating due to a lower density of the stretched beam compared with flat foils. Finally, it is shown that when multiPW laser pulse interacts with hydrogen solid ribbon, hole boring radiation pressure acceleration (RPA) dominates over the target normal sheath acceleration (TNSA). On the contrary, TNSA accelerates protons to higher energies in the case of polyethylene targets mainly due to its larger electron density compared with ionized solid hydrogen.

10241-57, Session 11

Numerical studies on alpha production from high-energy proton beam interaction with Boron

Stavros D. Moustaizis, Technical Univ. of Crete (Greece); Paraskevas Lalousis, Foundation for Research and Technology-Hellas (Greece) and Institute of Electronic Structure and Laser (Greece); Heinrich Hora, The Univ. of New South Wales (Australia); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and ELI Beamlines (Czech Republic) and Max-Planck-Institut für Quantenoptik (Germany)

Numerical investigations on high energy proton beam interaction with high density Boron plasma allows to simulate conditions concerning the alpha production from recent experimental measurements [1, 2]. The experiments measure the alpha production due to p11B nuclear fusion reactions when a laser-driven high energy proton beam interacts with Boron plasma produced by laser beam interaction with solid Boron. The alpha production and consequently the efficiency of the process depend on the initial proton beam energy, proton beam density, the Boron plasma density and temperature, and their temporal evolution. The main advantage for the p11B nuclear fusion reaction is the production of three alphas with total energy of 8.9 MeV, which could enhance the alpha heating effect and improve the alpha production. This particular effect is termed in the international literature as the alpha avalanche effect [3]. Numerical results using a multi-fluid, global particle and energy balance, code shows the alpha production efficiency as a function of the initial energy of the proton beam, the Boron plasma density, the initial Boron plasma temperature and the temporal evolution of the plasma parameters. The simulations enable us to determine the interaction conditions (proton beam – B plasma) for which the alpha heating effect becomes important.

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10241-58, Session PS

Multiparametric PIC simulations of electron vortices in laser plasma

Alexey R. Kniazev, Moscow Institute of Physics and Technology (Russian Federation) and P.N. Lebedev Physical Institute (Russian Federation); Kirill V. Lezhnin, Princeton Plasma Physics Lab. (United States); Sergei V. Soloviev, Moscow Institute of Physics and Technology (Russian Federation); Sergei V. Bulanov, National Institutes for Quantum and Radiological Science and Technology (Japan); Fedor F. Kamenets, Moscow Institute of Physics and Technology (Russian Federation); Timur Z. Esirkepov, National Institutes for Quantum and Radiological Science and Technology (Japan)

Using multiparametric 2D Particle-in-Cell simulations, we consider the evolution of electron vortices, coherent structures which may form during the interaction of high intensity laser radiation with underdense plasma. We study the instability causing the bending of the vortex boundary and consider the applicability of a snowplow model to the description of quasistatic evolution of electron vortices.

Conference 10242: Integrated Optics: Physics and Simulations

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10242-1, Session 1

Nanophotonics and hybrid plasmonics: different technologies and applications *(Invited Paper)*

Lech Wosinski, KTH Royal Institute of Technology (Sweden) and JORCEP, The Joint Research Ctr. of Photonics (China); Xu Sun, KTH Royal Institute of Technology (Sweden); Lars Thylén, KTH Royal Institute of Technology (Sweden) and JORCEP, The Joint Research Ctr. of Photonics (China)

Nanophotonics, especially CMOS-compatible silicon photonic technology has been successfully introduced for computer interconnects starting from large distances of hundreds of meters in data centers (e.g. active optical cables) down to optical backplanes in board-to-board communication inside a computer. Nevertheless, while silicon with a very high refractive index of guiding medium allows for fabrication of very compact devices, their feature sizes are still an order of magnitude larger than those of today's electronic integrated circuits and further miniaturization is restricted by diffraction limit of light. When increasing communication demands and large power density in multicore processors put serious bottleneck for conventional electrical wiring, optical interconnects, promising ultrahigh bandwidth, low latency and low energy consumption could be used instead. For inter- and intra-chip communication as well as for many lab-on-a-chip sensing applications one of the possible solutions is subwavelength optics based on surface plasmons, waves propagating along the dielectric-metal interfaces. In this way one can guide and control optical signals in nanoscale structures. Many plasmonic structures and solutions have been proposed and discussed for these applications, however all of them are suffering huge losses due to the proximity of metal surfaces. In a new solution, so called hybrid plasmonic (HP) structure, consisting of a metal layer, low refractive index gap and Si ridge, light is guided as a mixed mode, a coupling between photonic mode and plasmonic one. Due to both high-index contrast and plasmonic enhancement, the properties of HP waveguides, like neff and propagation loss can be easily tuned or adjusted according to the needs as they are very sensitive to the thickness of the low index layer. Light is guided with slightly relaxed confinement in comparison to plasmonic metal-insulator-metal structure, but still with subwavelength mode size, with acceptable level of propagation losses.

This paper gives a review of the recent progresses in our research on nanophotonics and hybrid plasmonic geometries, structures and devices. In the first part we present SOI-nanowire-based integrated components. The concept and different configurations of hybrid plasmonic structures will be then discussed. Finally different fabricated devices for applications in optical interconnects and sensing will be presented and characterized.

10242-2, Session 1

Biosensing using long-range surface plasmon waveguides *(Invited Paper)*

Oleksiy Krupin, Maryam Khodami, Hui Fan, Pierre Berini, Univ. of Ottawa (Canada)

Long-range surface plasmon waveguides, and their application to various transducer architectures for amplitude- or phase-sensitive biosensing, are discussed. Straight and Y-junction waveguides are used for amplitude detection, whereas Bragg gratings and single-, dual- and triple-output Mach Zehnder interferometers are used for phase detection. In either case, multiple-output biosensors provide means for referencing, which is very useful to eliminate common perturbations and drift. Performance assessments and sensing results are given in support of the approaches presented. The main points of differentiation relative to other optical approaches are emphasized. Application of the biosensors to disease detection in complex fluids, such as leukemia in patient serum samples, is demonstrated and discussed. Application to biomolecular interaction analysis and kinetics extraction are also demonstrated.

10242-3, Session 1

Plasmonic integrated circuit comprising metal waveguides, multiplexer/demultiplexer, detectors, and logic circuits on a silicon substrate

Mitsuo Fukuda, Masashi Ota, Asahi Sumimura, Shinya Okahisa, Motoki Ito, Yuya Ishii, Takeshi Ishiyama, Toyohashi Univ. of Technology (Japan)

We propose a plasmonic integrated circuit configuration comprising plasmonic devices and electronic devices, such as MOSFETs, in which plasmonic signals transmit data at high transfer rates, limited only by the optical propagation constant [1, 2]. The plasmonic and electronic devices in the integrated circuits are connected with plasmonic wavelength-division-multiplexing (WDM) circuits comprising metal wire [3] plasmonic multiplexers/demultiplexers [4], crossing metal wire [5], and plasmonic logic circuits [6] on the nanometer or micrometer scales.

To merge plasmonic and electronic device, we developed several types of plasmonic devices and signal transmission techniques [1-7]. To ensure that the plasmonic devices could be easily fabricated and monolithically integrated onto a silicon substrate using Si-MOSFET-compatible processes, the devices were fabricated on a silicon substrate and made from only silicon, silicon oxides, and metal; no other materials were used in device fabrication. The plasmonic and electric signals were transmitted on the same circuits, although the velocities of the two signals are different. The plasmonic signals were multiplexed using WDM techniques. Plasmonic WDM networks were easily fabricated by patterning silicon oxide films into waveguides and devices such as multiplexers [4]. The plasmonic WDM devices, such as waveguides, detectors, and multiplexers, operated in the 1300- and 1550-nm-wavelength bands that are typically employed in optical fiber transmission systems. Plasmonic logic circuits were formed by patterning a silicon oxide film on a metal film, and operation as a half adder was confirmed [5]. The calculated plasmonic signals and the plasmonic signals through the plasmonic WDM circuits, were directly converted to electric signals by connecting the plasmonic waveguides to MOSFET gates [1, 2] without any additional devices. Coherent detection techniques were also used to amplify plasmonic signals and increase the transmission distance [1, 2, 7]. This plasmonic integrated circuit will open a new stage of plasmonics.

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10242-4, Session 1

Gas sensing with a high-quality-factor photonic crystal ring resonator

Reyhaneh Jannesary, Institute for Microelectronics and Microsensors, Johannes Kepler Univ. Linz (Austria); Christian Ranacher, Cristina Consani, CTR Carinthian Tech Research AG (Austria); Thomas Grille, Infineon Technologies Austria AG (Austria); Bernhard Jakoby, Institute for Microelectronics and Microsensors, Johannes Kepler Univ. Linz (Austria)

Photonic crystals (PhCs) represent a periodic array of dielectric materials with different refractive indices, which can effectively control light propagation. A photonic crystal ring resonator (PCRR) can be formed by introducing a cavity in an equilatral hexagonal shape. The cavity is created by removing elements from the regular PhC grid. In this work we focus on a PCRR based on PhCs of silicon rods. The ring size can be adjusted to the desired resonance frequency.

In optical absorption spectroscopy, an analyte can be detected by the variation of light intensity due to absorption in analyte. The PhC parameters should be designed to create a mode whose wavelength matches the absorption peak of analyte and has high elecric field in the region filled by the analyte. In this work we present a design to enhance absorption of light by a fluid analyte being in contact with PCRRs. For this purpose, we propose a new PCRR with higher interaction between guided mode and analyte. This will be done in a PCRR consisting of dielectric silicon rods surrounded by air. The entire air space will replaced by the analyte when performing sensor tasks. The lattice constant and radius of the rods is tuned to obtain a resonance peak in desired frequency range. The band diagram gives the propagation modes and photonic band gap (PBG) of the photonic crystal structure, which supports TE polarized modes (electric field dominantly aligned along the silicon rods). The guided modes inside PBG region are related to the PCRR cavity. The Plane Wave Expansion (PWE) method is used to calculate the photonic band gap and propagating modes of structure.

Photonic crystal parameters should be designed to create a mode that has a high electric field in the region filled by the analyte. Achieving strong confinement of light intensity in the low index region is the advantage of this PCRR. In that manner, the interaction of light and analyte, which can be a liquid or a gas, will be enhanced. Structure optimization is performed by Finite Difference Time Domain (FDTD) simulations to maximize the Q-factor of the cavity mode at 0.2357μm-1. In our design, the radius of the twelve silicon rods at the corners of the outer and inner photonic crystal, is tuned to obtain the higher Q factor. The changes in the radii are ?r2 and ?r1 for outer and inner photonic crystals, respectively. The Q factor reaches a maximum of about 390000 for ?r1=0.22μm and ?r2=0.18μm. However, it decreases when the PCRR is coupled to waveguide.

The corresponding electric field profile of the mode at 0.2357μm-1 confirms that the cavity mode is strongly confined within the PCRR, having an effective mode volume equal to Veff =4.36μm3 and the ?, filling factor of optical field in the gas medium, is 0.759. Knowing the mode field overlap ?, the sensitivity of the device S to the refractive index change ?n can be estimated to 1700nm per refractive index unit (RIU).

10242-5, Session 1

Temperature-drift-secure wavelength meter based on an integrated micro ring resonator

Caterina Taballione, Univ. Twente (Netherlands); Temitope E. Agbana, Gleb V. Vdovin, Technische Univ. Delft (Netherlands); Marcel Hoekman, Lennart Wevers, LioniX BV (Netherlands); Jeroen Kalkman, Michel Verhaegen, Technische Univ. Delft (Netherlands); Peter J. M. van der Slot, Klaus-Jochen Boller, Univ. Twente (Netherlands)

Wavelength meters are central for many applications such as in telecommunication systems [1] or laser monitoring [2]. The primary function of a wavelength meter is to provide an output signal that changes sensitively with the wavelength of the input light. Of central importance is the reproducibility of the output signal even in the presence of external perturbations, e.g., temperature changes causing thermal drift. Various different methods are usually applied to improve reproducibility, e.g., thermal stabilization or repeated calibration with an additional reference light source of well-known and stable wavelength.

We present an integrated optical wavelength meter that is safe against thermal drift, requiring no thermal stabilization or repeated calibration with additional light sources. Our approach is based on an optically integrated waveguide micro ring resonator (MRR) together with a neural network-based readout and optimization algorithm that is able to detect temperature changes and reduce the effect of these on the displayed output wavelength. We implement this readout

method in an experimental setup comprising a tunable laser coupled into a Si3N4 waveguide MRR and a detector that measures the transmitted power. Via a applying a set of different heating voltages as a thermo-optical control parameter, the resonant wavelengths of the MRR are tuned to a set of different values. For measuring a single unknown input wavelength, the transmitted power is measured for the entire set of control parameters, i.e., an entire set of output powers is obtained per unknown wavelength from which the neural network determines the displayed wavelength.

We observe that this wavelength determination becomes increasingly more precise when increasing the number of heating voltages applied. We also observe that during the initial calibration of the MRR with a set of known input wavelengths, the readout precision increases with the number of known input wavelengths, and even with unknown input wavelengths.

We demonstrate for the first time the full working of such wavelength meter in that we observe long-term reproducibility (one week). We also observe that the displayed output wavelength does not change with ambient temperature up to several degrees. This shows that the readout provides temperature-drift secure operation of the wavelength meter, which makes a precise temperature stabilization or re-calibration after temperature change obsolete. The current wavelength range of operation spans one free spectral range (FSR) of the MRR (~2.7 nm) with a high spectral resolution of ~50 pm. An extension of the FSR is possible via exploiting waveguide birefringence of the MRR or using sequential resonators, e.g., in a Vernier fashion.

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10242-6, Session 2

Reconfigurable silicon photonics: devices and circuits *(Invited Paper)*

Daoxin Dai, Zhejiang Univ. (China)

As the link capacity increases dramatically, it is also becoming more and more important to develop smart photonic networks-on-chip so that the bandwidth/channels can be utilized optimally and flexible. One of the keys for realizing smart (reconfigurable) photonic networks is reconfigurable photonic integrated devices and circuits. As silicon has a large thermo-optic (TO) coefficient as well as the large heat conductivity (~149W/m?K), it is promising to realize efficient thermally-reconfigurable silicon photonic integrated devices and circuits with reduced power consumption and simple fabrication processes. This paper gives a review of our recent work on reconfigurable photonic integrated devices and circuits on silicon, including: (1) Ultra-broad band optical switches; (2) switchable/tunable silicon photonic integrated devices with transparent graphene nano-heaters; (3) Monolithically-integrated reconfigurable optical add-drop multiplexers (ROADMs) for wavelength-division-multiplexing (WDM) systems; (4) Multi-channel ROADMs mode-division-multiplexing (WDM) systems.

10242-7, Session 2

Automated tuning, control and stabilization of photonic integrated circuits *(Invited Paper)*

Francesco Morichetti, Andrea Annoni, Nicola Peserico, Douglas Oliveira De Aguiar, Emanuele Guglielmi, Giorgio Ferrari, Andrea I. Melloni, Politecnico di Milano (Italy)

The complexity scaling of silicon photonics circuits is raising novel needs related to control. Reconfigurable architectures need fast, accurate and robust procedures for the tuning and stabilization of their working point, counteracting temperature drifts originated by environmental fluctuations and mutual thermal crosstalk from surrounding integrated devices.

In this contribution, we report on our recent achievements on the automated tuning, control and stabilization of silicon photonics architectures. The proposed control strategy exploits transparent integrated detectors to monitor non-invasively the light propagating in the silicon waveguides in key spots of the circuit. Local monitoring enables the partitioning of complex architectures in small photonic cells that can be easily tuned and controlled, with need for neither preliminary circuit calibration nor global optimization algorithms.

Several examples of applications are presented that include the automatic reconfiguration and feedback controlled stabilization of an 8?8 switch fabric based on Mach-Zehnder interferometers (MZIs); the realization of a wavelength locking platform enabling feedback-control of silicon microring resonators for the realization of a 4?10 Gbit/s wavelength-division-multiplexing transmitter; on-chip all-optical reconstruction and unscrambling of mixed spatial modes by using a self-configuring mesh of silicon photonics MZIs. The effectiveness and the robustness of the proposed approach for tuning and stabilization of the presented architectures is demonstrated by showing that no significant performance degradation is observed under uncooled operation for the silicon chip.

10242-8, Session 2

On-chip optical frequency comb generation using linear mode locked laser with intracavity phase modulators

Mu-Chieh Lo, Robinson C. Guzmán Martínez, Muhsin Ali, Univ. Carlos III de Madrid (Spain); Rui Santos, Luc Augustin, SMART Photonics (Netherlands); Guillermo Carpintero, Univ. Carlos III de Madrid (Spain)

Mode-locked semiconductor lasers are robust and compact sources which can generate ultrafast pulses and coherent optical frequency combs. These are features of great interest in communications, sensing and biomedicine.

We present the experimental results on an integrated mode-locked semiconductor laser developed through a generic InP photonic integration platform. This technology enables monolithic active-passive integration, allowing advanced designs using high performance building blocks fabricated at a relatively low cost. The proposed design is a linear mode-locked laser, comprising a saturable absorber, gain sections, passive waveguide and multimode interference reflectors (MIR) in a symmetric arrangement as shown in Fig. 1. A new feature that we included in this device are symmetrically positioned intracavity phase modulators. Using MIR mirrors allows to have the optical outputs on chip, enabling further functionalities on the signal, as amplification though booster amplifiers. The device is demonstrated to generate an extremely broad optical spectrum, that constitutes an optical frequency comb. The phase locked nature of the comb is exhibited through autocorrelation traces, showing ultrafast pulses. The optical comb has a record 3 dB bandwidth of over 1.5 THz and the pulsewidth is under 1 ps as shown in Fig. 2 and 3.

10242-38, Session 2

Intra-band indirect photonic transition in a silicon slow light photonic crystal waveguide

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Photonic crystal (PhC) waveguides, fabricated on silicon, are appealing platforms due to their inherent flexibility in dispersion design as well as due to the compatibility with on-chip integration. Furthermore, the ability to dramatically enhance nonlinear effects by using slow light PhC waveguides combined with the strong confinement in these structures, facilitates the interactions on micro-meter length scales using picojoule pulses. In our work, by making use of a dispersion-engineered silicon photonic crystal waveguide, we report the first experimental demonstration of an intra-band indirect photonic transition in such device. The transition is driven by an optically generated free carrier front that moves along the waveguide and interacts with a co-propagating continuous wave (CW) probe wave in a 400 ?m long slow light waveguide. Upon interaction with the front, the probe wave packet, which initially propagates slower than the front, is accelerated and then escapes from the front. We also demonstrate a frequency upshift of the probe when it interacts with the leading edge of the front. We show here an intra-band transition with » 35% of the estimated theoretical efficiency, considering only the part of the CW probe that interacted with the front, at a refractive index change of only » 10-3. As we show, this phenomenon is also an optical event horizon. The presented effect opens new possibilities for frequency manipulation and all optical switching in optical telecommunication.

10242-9, Session 3

Parity-time symmetry optics for modal selection in transverse and longitudinal waves *(Invited Paper)*

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The evolving field of optics for information and communication is currently seeking directions to expand the data rates in all concerned devices, fiber-based or on chips. We describe here two possibilities where the new concept of PT-symmetry in optics [1,2] can be exploited to help high data rate operation, considering either transverse or longitudinal aspects of modal selection, and assuming that data are carried using precise modes.

The first aspect is transverse multimode transport. In this case, a fiber or a waveguide carries a few modes, say 4 to 16, and at nodes, they have to undergo a demux/mux operation to add or drop a subset of them, as much as possible without affecting the others. We shall consider to this end the operation as described in ref. [3] : if a PT-symmetric "potential", which essentially consists of a transverse gain-loss profile with antisymmetry, is applied to a waveguide, it has a very different impact on the different modes and mode families in the waveguide. One can in particular find situations where only two modes of the passive waveguide to be analyzed may enter into a gain regime, and not the other ones. From this scheme and others [4], we will discuss what is the road left towards an actual device, either in dielectrics or in case plasmonics is envisioned [5], i.e. with rather constant losses, but the possible advantage of miniaturization.

The second aspect is longitudinal mode selection. The special transport properties of PT-symmetric Bragg gratings are now well established. In order to be used within a data management system, attention has to be paid to the rejection rate of Bragg gratings, and to the flatness of their response in the targeted window. To this end, a slow modulation of both real and imaginary parts of the periodic pattern of the basically PT-symmetric waveguide can help, in the general spirit of "apodization", but now with more parameters. We will detail some aspects of the designs introduced in [6] , notably their ease of implementation in established optoelectronic fabrication platforms.

To conclude these considerations, the perspectives offered by the combination of transverse multimode systems and PT-symmetric type of periodicity will be discussed.

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10242-10, Session 3

Active functional devices using parity-time symmetry optics

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The progress of nanotechnologies has triggered the emergence of many photonic artificial structures: photonic crystals, metamaterials, plasmonic resonators. Recently the intriguing class of PT-symmetric devices, referring to Parity-Time symmetry [1] has attracted much attention. The characteristic feature of PT-symmetry is that the structures' refractive index profile is complex-valued due to the presence of alternating gain and loss regions in the system. Apart from fundamental research motivations, the tremendous interest in these artificial systems is strongly driven by the practical outcomes expected to foster a new generation of tunable, reconfigurable and non-reciprocal devices.

The principle of gain-loss modulation lying in the heart of PT-symmetry optics enables a range of innovative solutions in the field of integrated optics at 1.5µm [2-7]. By using PT-symmetric coupled waveguides and Bragg reflectors as fundamental building blocks, it is possible to build a wide variety of functional optical devices. The PT-symmetry principle provides an alternative way for the realization of active devices that could become functional in a new platform for integrated optics. For instance one major bottleneck of the III-V/Si hybrid integration approach is that each type of active devices (laser, modulator, etc) requires a specific composition of III-V semiconductor alloy, involving a variety of (re) growth challenges. The advantage of the PT-symmetry solution is that the fabrication of all these devices can be done with a single stack of III-V semiconductor alloys that greatly simplifies the technological process.

The aim of the current contribution is to provide a survey of the most promising applications of PT-symmetry in photonics with a particular emphases on the transition from theoretical concepts to experimental devices. The intention is to draw attention to the risks and issues related to the practical implementation that are most often overlooked in the basic theoretical models. An analysis of solutions to circumvent or overcome these issues to achieve a proper devices operation will be presented. Preliminary results on the experimental realization of PT symmetric structures using III-V's technology will be communicated.

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10242-11, Session 4

Design of optical metamaterial waveguide structures *(Invited Paper)*

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Subwavelength gratings (SWGs) are periodic structures with a pitch (?) smaller than the wavelength of the propagating wave (?), so that diffraction effects are suppressed. These structures thus behave as artificial metamaterials where the refractive index and the dispersion profile can be controlled with a proper design of the geometry of the structure. SWG waveguides have found extensive applications in the field of integrated optics, such as efficient fiber-chip couplers, broadband multimode interference (MMI) couplers, polarization beam splitters or evanescent field sensors, among others. From the point of view of nano-fabrication, the subwavelength condition (? << ?) is much easier to meet for long, mid-infrared wavelengths than for the comparatively short near-infrared wavelengths. Since most of the integrated devices based on SWGs have been proposed for the near-infrared, the true potential of subwavelength structures has not yet been completely exploited. In this talk we summarize some valuable guidelines for the design of high performance SWG integrated devices. We will start describing some practical aspects of the design, such as the range of application of semi-analytical methods, the rigorous electromagnetic simulation of Floquet modes, the relevance of substrate leakage losses and the effects of the random jitter, inherent to any fabrication process, on the performance of SWG structures. Finally, we will show the possibilities of the design of SWG structures with two different state-of-the-art applications: i) ultra-broadband MMI beam splitters with an operation bandwidth greater than 300nm for telecom wavelengths and ii) a set of suspended waveguides with SWG lateral cladding for mid-infrared applications, including low loss waveguides, MMI couplers and Mach-Zehnder interferometers.

10242-12, Session 4

Broadband high-efficiency zero-order surface grating coupler for the near- and mid-infrared wavelength ranges

Alejandro Sánchez-Postigo, Juan Gonzalo Wangüemert-Pérez, José M. Luque-González, Iñigo Molina-Fernández, Univ. de Málaga (Spain); Pavel Cheben, National Research Council Canada (Canada); Carlos A. Alonso-Ramos, Univ. Paris-Sud (France) and Univ. Paris-Saclay (France); Robert Halir, Univ. de Málaga (Spain); Jens H. Schmid, National Research Council Canada (Canada); Alejandro Ortega-Moñux, Univ. de Málaga (Spain)

Efficient light coupling from a chip into an optical fiber is a major issue in silicon photonics, as the dimensions of silicon-on-insulator (SOI) waveguide cores, whose cross-section is of 500 nm x 220 nm, are reduced compared to conventional single-mode optical fiber diameters. Surface grating couplers are between the most commonly used devices to address the coupling problem. They consist of a waveguide with a periodic perturbation that radiates the input power towards the optical fiber. Unlike edge couplers, they allow wafer scale integration, can be allocated anywhere on the chip and avoid chip facet polishing

[1]. However, since the radiation angle is strongly dependent on the wavelength, conventional surface grating couplers cannot offer high coupling efficiency and broad bandwidth simultaneously. Bandwidth requirements are crucial, not only at near-infrared, where communications demand greater number of allocated channels, but also for the mid-infrared spectral band to cover a wider fingerprint molecule range. Zero-order surface grating couplers have been recently proposed to circumvent the intrinsic bandwidth limitations of conventional surface grating couplers [2]. These devices, which use the 0 instead of the -1 diffraction order, use a subwavelength engineered waveguide and a high index upper material to radiate upwards with both high efficiency and broad bandwidth. The upper material is separated from the waveguide core by a cladding layer of an epoxy resin or a matching gel. In zero-order grating couplers, the radiation angle is the main factor that governs the bandwidth, so that the lower the angle, the larger the bandwidth. On the other hand, the coupling efficiency is related to the cladding thickness. Therefore, we utilize a two-step design procedure. First, the bandwidth is enlarged by reducing the grating radiation angle with a judicious subwavelength grating engineering. Then, the cladding layer is linearly apodized to increase the overlap integral between the radiated field and the Gaussian-like fiber mode. In this work, we present several zero-order grating coupler devices based on different upper materials, such as silicon or germanium, which have been designed for both the near-infrared and the mid-infrared wavelength ranges (? = 1.55 µm and ? = 3.8 µm, respectively). Our simulations report on sub-decibel coupling efficiencies (below 0.8 dB in all cases) and 3-dB bandwidths greater than 200 nm for the near-infrared and 900 nm for the mid-infrared.

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10242-13, Session 4

Possibilities of Bragg filtering structures based on subwavelength grating guiding mechanism

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Silicon-on-insulator (SOI), as the most promising platform, for advanced photonic integrated structures, employs a high refractive index contrast between the silicon “core” and surrounding media. One of the recent new ideas within this field is based on the alternative formation of the subwavelength sized (quasi)periodic structures, manifesting as an effective medium with respect to propagating light. Such structures relay on Bloch wave propagation concept, in contrast to standard index guiding mechanism. Soon after the invention of such subwavelength grating (SWG) waveguides, the scientists concentrated on various functional elements such as couplers, crossings, mode transformers, convertors, MMI couplers, polarization converters, resonators, Bragg filters, and others. Our contribution is devoted to a detailed numerical analysis and design considerations of Bragg filtering structures based on SWG idea. Based on our previous studies where we have shown impossibility of application of various 2 and “2.5” dimensional methods for the proper numerical analysis, here we effectively use two independent but similar in-house approaches based on 3D Fourier modal methods, namely aperiodic rigorous coupled wave analysis (aRCWA) and bidirectional expansion and propagation method based on Fourier series (BEX) tools. As it was recently demonstrated, SWG Bragg filters are feasible. Based on this idea, we propose, simulate, and optimize spectral characteristics of such filters. In particular, we have investigated several possibilities of modifications of original SWG waveguides towards the Bragg filtering, including firstly - simple single-segment changes in position, thickness, and width, and secondly - several types of Si inclusions, in terms of perturbed width and thickness (and their combinations). The leading idea was to obtain required (e.g. sufficiently narrow) spectral characteristic while keeping the minimum size of Si features large enough. We have found that the second approach with the single element perturbations can provide promising designs. Furthermore, even more complex filtering SWG structures can be considered.

10242-14, Session 5

Nonlinear dynamics of optical frequency combs *(Invited Paper)*

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One of the most spectacular applications of nonlinear integrated optics is that of nonlinear microresonator based optical frequency comb light sources. Optical comb sources are characterized by a spectrum comprising many equally spaced frequency components, and possess a wide range of scientific and technological applications. Although commercial comb generators are based on mode-locked lasers and fiber supercontinuum generation, nonlinear integrated optics provides a low-cost and chip-scale alternative, based on a low-power cw pump laser coupled into a high-Q microresonator. So far, microresonator frequency combs have mostly exploited materials with third order Kerr nonlinearity, which permits to generate successive comb lines with a spacing equal to the resonator free-spectral range via multiple four-wave mixing. Modeling of microresonator frequency combs can be greatly simplified by means of a single partial differential equation approach, in analogy with the case of other types of coherently driven Kerr spatially diffractive or temporally dispersive nonlinear cavities. In order to lower the threshold pump power, and to extend the spectral range of frequency comb generation, for example into the visible or mid-infrared, while still using near-infrared cw laser pumps, quadratic nonlinear cavities can be usefully exploited. Efficient quadratic microresonator frequency comb sources should operate close to the phase-matching condition for the underlying quadratic processes. On the other hand, when operating in the cascading regime, quadratic comb dynamics reduces to the Kerr case. Quite remarkably, a single time domain partial differential equation with an effective delayed third-order nonlinearity may also be derived to describe with excellent accuracy the dynamics of quadratic frequency comb generation. Formally similar equations are obtained under different phase-matching conditions that lead, for example, to either intracavity second-harmonic generation or to optical parametric oscillation. In more general situations where multiple phase-matched wave mixing processes are present, and the frequency combs generated around the interacting waves over multiple octaves overlap, numerical modeling may usefully exploit a single envelope equation approach. This formalism permits to naturally include the simultaneous presence of quadratic and cubic nonlinearities in the modeling of the comb dynamics.

10242-15, Session 5

On-chip frequency combs for complex quantum state preparation *(Invited Paper)*

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Yaron Bromberg, Yale Univ. (United States); Lucia Caspani, Heriot-Watt Univ. (United Kingdom); David J. Moss, Swinburne Univ. of Technology (Australia); Roberto Morandotti, Institut National de la Recherche Scientifique (Canada)

The on-chip generation of optical quantum states will enable accessible advances for quantum technologies. We demonstrate that integrated quantum frequency combs (based on high Q microring resonators made from a CMOS-compatible, high refractive index, doped glass platform) can enable the generation of pure heralded single photons, cross-polarized photon pairs, as well as bi- and multi-photon entangled qubit states over a broad frequency comb covering the S, C, L telecommunications band, with photon frequencies corresponding to standard telecommunication channels spaced by 200 GHz.

Exploiting a self-locked, intra-cavity excitation configuration, a highly stable source of multiplexed heralded single photons is demonstrated, operating continuously for several weeks with less than 5% fluctuation. The photon bandwidth of 110 MHz is compatible with quantum memories, and high photon purity was confirmed through single photon auto-correlation measurements. In turn, by simultaneously exciting two orthogonal polarization mode resonances, we demonstrate the first realization of type II spontaneous FWM (in analogy to type II spontaneous parametric down-conversion), allowing the direct generation of orthogonally polarized photon pairs on a chip.

By using double pulse excitation, we demonstrate the generation of time-bin entangled photon pairs. We measure qubit entanglement with visibilities above 90%, enabling the implementation of quantum information processing protocols. Finally, the excitation field and the generated photons are intrinsically bandwidth matched due to the resonant characteristics of the ring cavity, enabling the multiplication of Bell states and the generation of a four-photon time-bin entangled state. We confirm the generation of this four-photon entangled state through four-photon quantum interference.

10242-16, Session 5

Simplified model enabling optimization of silicon modulators

Diego Pérez-Galacho, Delphine Marris-Morini, Ctr. de Nanosciences et de Nanotechnologies (France); Remco Stoffer, PhoeniX B.V. (Netherlands); Eric Cassan, Ctr. de Nanosciences et de Nanotechnologies (France); Charles Baudot, STMicroelectronics (France); Twan Korthorst, PhoeniX B.V. (Netherlands); Frédéric Boeuf, STMicroelectronics (France); Laurent Vivien, Ctr. de Nanosciences et de Nanotechnologies (France)

Silicon photonics is nowadays the reference platform for many applications like sensing and telecommunications. Its natural CMOS compatibility enables the co-integration with current microtechnology circuitry. This feature makes it attractive for next generation photonics based technology, like optical interconnects. Silicon phase modulators are normally key devices in many applications, like sensors and transmitters. However, depending on the targeted application, modulators' specifications change completely. In sensing, low loss and high efficiency are required. However, in telecommunications bandwidth is normally the crucial parameter. Optimizing a modulator for a given applications requires many simulation iterations during the design stage. However, simulating a modulator requires a lot of memory and long computation times, in the order of 30 min for a conventional lateral PN junction based modulator. These long simulation times hinder the optimization of the modulator in a reasonable time. In this design stage, a proper modeling of the modulator is of great importance in order to overcome those constraints. In this work we propose a simplified model for silicon modulators that relax those constraints, without requiring TCAD simulations yet maintaining a good level of accuracy. Using the model, the simulation time of a conventional lateral PN junction based modulator is below 1min, meaning one order of magnitude improvement. Moreover, the relative error of the model compared to a full-physical simulation is below 5%.

10242-17, Session 5

Continuous-wave second and third harmonic generation in high-Q gallium nitride photonic crystal cavities on silicon *(Invited Paper)*

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Wide bandgap semiconductors such as gallium nitride (GaN) are expected to be essential constituents of future optical circuits, as their optical response can accommodate a broad wavelength range while suppressing two-photon absorption and free-carrier absorption effects that are encountered with silicon (Si) structures. Their direct wide bandgap is also favourable for the incorporation of active elements. Furthermore, nonlinear optical processes can be harnessed by exploiting the higher-order susceptibility tensors of the crystal structure to achieve advanced light control modalities, enabling all-optical processing and the generation of entangled photon states. Towards that purpose, two-dimensional photonic crystals (PhC) provide the necessary means to control the propagative and dispersive behaviour of light in planar semiconductor layers.

We will report on nonlinear frequency conversion from the telecom range via second harmonic generation (SHG) and third harmonic generation (THG) in suspended gallium nitride slab photonic crystal (PhC) cavities on silicon, under continuous-wave resonant excitation.

Genetic optimization is applied to sweep parameter space for the highest cavity quality factors, and simultaneously accounting for power in-coupling. While there is a clear trade-off theoretically between coupling efficiency and Q-factor for a given cavity design, the upper limit on the Q-factor that is imposed by loss channels, given the disorder figure of current fabrication technology, makes room for introducing improved far-field coupling to enhance nonlinear processes without sacrificing the experimentally achievable light confinement. Far-field coupling is addressed through various PhC cavity designs, which enable the excitation of the fundamental mode with a Gaussian beam.

Optimized two-dimensional PhC cavities with augmented far-field coupling have been characterized with quality factors as high as 44'000, approaching the computed theoretical values. The strong enhancement in light confinement has enabled second harmonic generation (SHG) under continuous-wave excitation, with up-conversion from both 1300 nm and 1550 nm wavelength bands, confirmed by spectral and power dependence measurements. At 1550 nm, normalized SHG conversion efficiency as large as 2.4?10^-3 W^-1 are measured as well as simultaneous THG. SHG emission power of up to 0.74 nW has been detected without saturation.

The results herein validate the suitability of gallium nitride for integrated nonlinear optical processing.

10242-18, Session 5

Silicon and germanium free carrier injection modulators for the mid-infrared *(Invited Paper)*

Milos Nedeljkovic, Goran Z. Mashanovich, Univ. of Southampton (United Kingdom)

We present our latest results on experimental demonstrations of free carrier injection modulators based on Silicon-on-Insulator and Germanium-on-Silicon waveguide platforms operating at a mid-

infrared wavelength of 3.8 μm. The simulation, design, fabrication, and experimental characterisation processes will be discussed, as well as the prospects for using these devices at longer mid-infrared wavelengths.

10242-19, Session 6

Nanoantenna enhanced terahertz radiation: matter interaction *(Invited Paper)*

Luca Razzari, Institut National de la Recherche Scientifique (Canada)

In the past few years, we have shown that terahertz (THz) resonant dipole nanoantennas are effective in confining the radiation on a deep sub-wavelength scale, with a significant field enhancement in close proximity of the nanoantenna ends [1,2]. More recently, we have investigated the end-to-end coupling of THz nanoantennas in chains separated by extremely narrow gaps (down to 20 nm in width). We have found that this configuration enables a giant THz field enhancement (> 1,000) within such gaps. These distinctive properties can be exploited for enhancing the interaction of THz radiation with nanomaterials and molecules. Indeed, the effective absorption of an object scales with the square of the local electric field, and it can thus be significantly amplified within antenna nanocavities. In our investigation, we have explored the coupling of semiconducting nanocrystals with arrays of nanoantenna chains featuring gaps of about 20 nm. When the resonance of the nanoantenna array is matched to the phonon resonance of the nanocrystals, the interaction between the two systems leads to a clear interference in the THz far-field response. This effect has been first exploited to perform enhanced THz spectroscopy of a single layer of cadmium selenide quantum dots [3]. Other investigations are ongoing and will be presented on site.

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10242-20, Session 6

Pockels effect in strained silicon photonics *(Invited Paper)*

Laurent Vivien, Mathias Berciano, Pedro Damas, Guillaume Marcaud, Xavier Le Roux, Ctr. de Nanosciences et de Nanotechnologies (France); Paul Crozat, Ctr. for Nanosciences et de Nanotechnologies (France); Carlos A. Alonso-Ramos, Daniel Benedikovic, Delphine Marris-Morini, Eric Cassan, Ctr. de Nanosciences et de Nanotechnologies (France)

Silicon photonics has generated a strong interest in recent years, mainly for optical communications and optical interconnects in CMOS circuits. The main motivations for silicon photonics are the reduction of photonic system costs and the increase of the number of functionalities on the same integrated chip by combining photonics and electronics, along with a strong reduction of power consumption. However, one of the constraints of silicon as an active photonic material is its vanishing second order optical susceptibility, the so called ?(2) , due to the centrosymmetry of the silicon crystal. To overcome this limitation, strain has been used as a way to deform the crystal and destroy the centrosymmetry which inhibits ?(2). The paper presents the recent advances in the development of second-order nonlinearities including discussions from fundamental origin of Pockels effect in silicon until its implementation in a real device. Carrier effects induced by an electric field leading to an electro-optics behavior will also be discussed.

10242-21, Session 6

Functional oxides induced strain for silicon photonics applications

Guillaume Marcaud, Sylvia Matzen, Carlos A. Alonso-Ramos, Xavier Le-Roux, Mathias Berciano, Valérie Pillard, Pedro Damas, Thomas Maroutian, Guillaume Agnus, Ludovic Largeau, Eric Cassan, Delphine Marris-Morini, Philippe Lecoeur, Laurent Vivien, Ctr. de Nanosciences et de Nanotechnologies (France)

Silicon photonics is expected to allow the implementation of a wide range of applications including sensing, datacom and security with the potential to leverage the already existing CMOS fabrication facilities for cost-effective and large production. Among the building blocks to develop, optical modulator is considered as a key device for integrated circuits. The main physical effect to perform optical modulation in silicon is based on plasma dispersion effect. However the maximum modulation speed achievable with this approach is limited by the mobility and recombination time of the carriers. Furthermore, these types of modulators face some limitations in terms of power consumption, chirp and loss that may compromise their future integration in integrated circuits.

The purpose of this work is to explore an alternative approach, based on the use of the Pockels effect. Such an effect, commonly used in Lithium-Niobate, allows high speed and low power consumption optical modulation. Unfortunately silicon is a centro-symmetric crystal leading to a vanishing of the second order nonlinear coefficient, i.e. no Pockels effect. To overcome this limitation, it is possible to break the crystal symmetry by straining the silicon lattice. The new approach developed here is to generate strain by the epitaxial growth of crystalline functional oxides, which exhibit more appropriate strain-induced characteristics in silicon than the use of silicon nitride with lower defect concentration at the Si/oxide interface. Indeed, these functional oxides are deposited by epitaxial growth at high temperature on silicon with pulsed-laser deposition. The induced strain due to lattice parameter mismatch and the difference in the thermal expansion coefficients between oxides and silicon are strong. Furthermore, these functional oxides exhibit very interesting multiferroicity and piezoelectricity properties that paves the way to a new route to implement silicon photonic circuits with unprecedented functionalities.

Last results on the integration of high quality oxides on silicon waveguides will be presented as well as a full characterization of the strain-induced property changes including X-ray diffraction, AFM-SEM microscopies, and Raman spectroscopy. The first experiments of light propagation in hybrid oxides on silicon photonic structures will be also reported.

10242-22, Session 6

Astrophotonics: the application of photonic technology to astronomy

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Astrophotonics is the application of photonics to astronomical instrumentation. This developing field is a significant departure from the traditional approach to astronomical instrumentation. Astronomical instruments typically employ bulk optics, such as lenses, mirrors, diffraction gratings and filters to manipulate beams of light, which propagate in free-space between the optics. Astrophotonic instruments replace such bulk optics with devices embedded in optical fibres, planar and three-dimensional waveguides, such that the manipulation of light takes place within the waveguides themselves. This allows improvements in efficiency, functionality and scalability of astronomical instruments.

I will review recent developments in astrophotonics, focussing on those devices using integrated optics. In particular I will discuss our recent research into the use microring-resonators for wavelength calibration, wavelength filtering and Doppler planet searches, as well as briefly review the use of array waveguide gratings for spectroscopy, and beam combiners for interferometry.

To be useful for astronomy such devices must have large free spectral range (up to 300 nm), and have very low insertion losses. One of the major challenges of astrophotonics is the efficient coupling of integrated optics with mode field diameters of ~1 micron to the beam of a telescope. I will discuss these challenges, solutions and possible future directions for astrophotonic instruments.

10242-23, Session 6

Distributed meandering waveguides for novel photonic circuits

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Meandering waveguide distributed feedback structures are novel integrated photonic lightwave and microwave circuit elements. Meandering waveguide distributed feedback structures with a variety of spectral responses can be designed for a variety of lightwave and microwave circuit element functions. Distributed meandering waveguide (DMW) structures [1] show a variety of spectral behaviors with respect to the number of meandering loop mirrors (MLMs) [2] used in their composition as well as their internal coupling constants (Cs). DMW spectral behaviors include Fano resonances, coupled resonator induced transparency (CRIT), notch, add-drop, comb, and hitless filters. What makes the DMW special is the self-coupling property intrinsic to the DMW's nature. The basic example of DMW's nature is motivated through the analogy between the so-called symmetric meandering resonator (SMR), which consists of two coupled MLMs, and the resonator enhanced Mach-Zehnder interferometer (REMZI) [3]. A SMR shows the same spectral characteristics of Fano resonances with its self-coupling property, similar to the single, distributed and binary self coupled optical waveguide (SCOW) resonators [4].

So far DMWs have been studied for their electric field intensity, phase [5] and phasor responses [6]. The spectral analysis is performed using the coupled electric field analysis and the generalization of single meandering loop mirrors to multiple meandering distributed feedback structures is performed with the transfer matrix method. The building block of the meandering waveguide structures, the meandering loop mirror (MLM), is the integrated analogue of the fiber optic loop mirrors. The meandering resonator (MR) is composed of two uncoupled MLM's. The meandering distributed feedback (MDFB) structure is the DFB of the MLM. The symmetric MR (SMR) is composed of two coupled MLM's, and has the characteristics of a Fano resonator in the general case, and tunable power divider or tunable hitless filter in special cases. The antisymmetric MR (AMR) is composed of two coupled MLM's. The AMR has the characteristics of an add-drop filter in the general case, and coupled resonator induced transparency (CRIT) filter in a special case. The symmetric MDFB (SMDFB) is composed of multiple coupled MLM's. The antisymmetric MDFB (AMDFB) is composed of multiple coupled MLM's. The SMDFB and AMDFB can be utilized as band-pass, Fano, or Lorentzian filters, or Rabi splitters.

Distributed meandering waveguide elements with extremely rich spectral and phase responses can be designed with creative combinations of distributed meandering waveguides structures for various novel photonic circuits.

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10242-24, Session 7

Trimming of ring resonators via ion implantation in silicon *(Invited Paper)*

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Ion implantation into silicon causes radiation damage. If a sufficient dose is implanted, complete amorphisation can result in any implanted part of an optical device device. Amorphous silicon has a refractive index that is significantly different higher than that of crystalline silicon (~10-1), and can therefore form the basis of a refractive index change in optical devices. This refrective index change can be partially or completely removed by annealing. In recent years we have presented results on the development of erasable gratings in silicon to facilitate wafer scale testing of silicon photonics circuits. These gratings are formed by amorphising selected areas of silicon by utilising ion implantation of Germanium. However, we have now used similar technology for trimming of integrated photonic components. In this paper we discuss design, modelling and fabrication of ring resonators and their subsequent trimming using ion implantation of Germanium into silicon followed by annealing

10242-25, Session 7

Polymer optical waveguide devices for mode-division-multiplexing applications *(Invited Paper)*

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Mode-division multiplexing (MDM), which allows different guided modes of a few-mode fiber to carry different signals, is a new technology being actively pursued worldwide to increase the signal-carrying capacity of a fiber. For the development of the MDM technology, many mode-controlling devices are needed, such as mode converters, mode (de) multiplexers, mode filters, and mode switches. Among the various technologies available for the implementation of such devices, the polymer waveguide technology offers some distinct advantages. First, the polymer waveguide fabrication process based on photolithography can produce highly precise waveguide structures, which is essential for the realization of devices that involve phase matching, such as gratings and asymmetric directional couplers. Second, it is easy to form multilayer and three-dimensional (3D) waveguide structures with polymer, such as vertical couplers and branches. 3D polymer waveguide optics provides a particularly flexible platform for the development of devices for the manipulation of fiber modes, which are 3D in nature. Third, the large thermo-optic coefficient of polymer can be explored for the realization of tunable devices and switching devices. Fourth, being low-index-contrast structures, polymer waveguides can be easily designed to match the dimensions of few-mode fibers and thus minimize the fiber-waveguide coupling loss. On the other hand, high-index-contrast waveguides (such as silicon photonics) do not allow direct butt-coupling to few-mode fibers. This paper presents a review of the polymer waveguide devices for MDM applications developed at the City University of Hong Kong, which include grating-based mode converters and (de)multiplexers, 3D mode (de)multiplexers, and graphene-based mode filters.

10242-26, Session 7

Predicting the yield of photonic integrated circuits using statistical compact modeling *(Invited Paper)*

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In recent years, significant progress has been made in the development of design flows for photonic integrated circuits, in many cases, by taking advantage of the mature capabilities already available in electronic design automation (EDA). While some aspects of EDA workflows have been easily ported to photonics, others, such as repurposing standard circuit simulation tools like SPICE to simulate the response of photonic integrated circuits, have been less successful. As a result, dedicated photonic circuit simulators have been developed and process design kits for currently-available photonic design flows now include validated compact model libraries to perform photonic circuit simulations as well as co-simulation between electrical and photonic circuits. Despite these advances, detailed statistical analysis is not yet supported by these photonic circuit simulators as the requirements for photonics are similar yet importantly different than for electronics. For example, a typical approach to statistical analysis in electronics that is highly portable to photonics is to separate the contributions of process and mismatch variations, where all statistical parameters vary either identically or in a completely uncorrelated manner for a given circuit. Conversely, small layer thickness variations, which may be unimportant for many electrical components, can lead to variations in waveguide effective and group indices that are correlated over length scales of hundreds of microns or more. Thus, components such as ring modulators can have key parameters such as resonant wavelength or free spectral range that are correlated over large distances with correlation coefficients that depend on the distance between them. Similarly, Mach-Zehnder interferometers composed of long waveguides can have very different statistical properties depending on the path separation of the waveguide arms on the wafer. We will review the state-of-the-art approaches used in the statistical modeling of photonic integrated circuits and show how they can be used to predict the yield.

10242-27, Session 7

Polarization insensitive Ge-rich silicon germanium waveguides for optical interconnects on silicon

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Continuously increasing data traffic is pushing communications systems and data centers to their limits. New solutions are thus needed for low power consumption and large bandwidth optical communications systems. In this context, a CMOS compatible photonic platform is of a great interest, to take advantage of the mature and low cost Si based technology. Germanium is a promising candidate for a unified photonic platform on silicon. Ge pseudo direct gap properties are used for the realization of efficient modulators and photodetectors with remarkable high speed and low power consumption. However, as Si and Ge have 4% lattice mismatch, straightforward integration of high quality active devices with passive circuitry is difficult due to high dislocation rate. Hence, to efficiently accommodate Si and Ge lattice parameters an integration scheme based on a graded buffer layer can be used. With this approach, we recently have shown that light can be confined in Ge-rich SiGe layer on top of a graded buffer, to obtain low loss waveguide on bulk silicon substrate. Hence, the integration of Ge based active devices becomes possible: germanium quantum well active region embedded in a PIN diode can be grown on Ge-rich Si1-yGey virtual substrate that acts also as a guiding layer. Typically y higher than 0.8 guarantees a high quality of the Ge-rich active region. Moreover, we have demonstrated experimentally the possibility to obtain compact 90° turns and Mach-Zehnder interferometers by tuning the light confinement. Indeed, low loss slightly etched waveguides for straight sections were combined with low radiation loss deeply etched waveguides to obtain a low footprint device. In this work, we now show that these Ge-rich Si1-yGey waveguides can also solve the problem of polarization dependence which is inherent to integrated photonic circuits. A detailed study of waveguide geometries is performed to find optimal parameters for low polarization sensitivity single-mode waveguides at ?=1.55µm. Optimized geometries are tolerant to fabrication errors. The difference in effective indexes between fundamental TE and TM modes does not exceed 5*10-5 even with a variation of 10 nm of the etching depth of the waveguides, which is larger than the typical tolerance in CMOS foundries. The polarization dependence of the group index and dispersion coefficient has also been studied. Based on these waveguides, passive structures such as multimode interference structures (MMI) and Mach Zehnder interferometers have been designed simultaneously for TE and TM polarizations. These results pave the way for Ge-rich SiGe polarization insensitive passive circuitry on bulk silicon substrate.

10242-28, Session 7

FDTD simulation of amorphous silicon waveguides for microphotonics applications

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During recent years, hydrogenated amorphous Silicon (a-Si:H) has been reported by many authors as a possible candidate for being used in mass production of photonics circuits. State of the art good quality a-Si:H can be deposited by Pressure Enhanced Chemical Vapor Deposition (PECVD). This technique has reached a stable maturity and quality, due to the large investment directed to mass production of a-Si:H solar cells and thin film transistor for active matrix flat panel displays. It is possible to produce good quality a-Si:H at low temperatures (between 200 and 400 ºC), making amorphous silicon deposition compatible with back-end CMOS processing. The amorphous phase of silicon has been intensively studied during the last decade of the XX century and it is well known that the electronic and optical properties of the films are strongly influenced by deposition technique and conditions. The presence of defects and dangling bonds in the lattice results in a high density of localized states at energies below the energy gap, producing photon absorption in the near IR range at telecommunication wavelengths. Optimal refractive index of a-Si:H, measured by reflectometry, is 3.65 at 1550 nm which is an higher value than the crystalline silicon correspondent. However, hydrogen concentration is strongly dependent on deposition temperature and determines sub-gap absorption coefficient, producing small variations of the amorphous silicon optical functions. Dependence of the material characteristics on the specific deposition conditions should be considered a real possibility and taken into account in waveguide design stage, together with geometric variability.

In this work we correlate the dimension of the waveguide with small variations of the refractive index of the material used for the waveguide core. We calculate the effective modal refractive index for different dimensions of the waveguide and with slightly variation of the refractive index of the core material.

These results are used as an input for a set of Finite Difference Time Domain (FDTD) simulation, realized with the OptiFDTD 32bit freely available simulator, directed to study the characteristics of amorphous

silicon waveguides embedded in a SiO2 cladding. The study considers simple linear waveguides with rectangular section for studying the modal attenuation expected at different wavelengths. Finally, waveguides with a 90º degrees circular bending are studied; for outlining the waveguide curvature radius influence on the transmission attenuation. Transmission efficiency is determined analyzing the decay of the light power along the waveguides.

As far as near infrared wavelengths are considered, a-Si:H shows a highly dependent frequency behavior. Its extinction coefficient rapidly increases as operating frequency goes into visible spectrum range. Power decay due to decreasing of curvature radius does not seem to represent a serious constraint. This means that, although the designer must keep it in mind, radiation losses should remain within acceptable limits when considering arc's radius as small as 3 μm at its most.

10242-29, Session 7

Microstructured coupling elements for 3D silicon optical interposer

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Current trends in electronic systems, such as Internet of Things and Cloud Computing, call for high interconnect bandwidth, increased number of devices and high IO count. The integration of optical waveguides on wafer and board level becomes an alternative approach to cope with the performance demands. Moving towards fully optical systems, to reduce the opto-electrical conversion, optical chip-to-chip and chip-to-board communication on interposer-level are required. Currently planar optical waveguides and optical through silicon vias (TSVs) respectively horizontal or vertical interconnection are discussed for interposer. They can easily be fabricated, but there is a lack of coupling elements for connecting both waveguide structures. So a simple integration of (electro)-optical devices and optical networks on waveguides could be possible, if coupling mechanisms are integrated in waveguides. The goal of this work is to develop coupling elements to aid 3D optical interconnect network on interposer-level. Two micro-structuring technologies for integration of coupling elements with horizontal and vertical waveguides are investigated: μ-mirror fabrication by imprint (i) and dicing technique (ii).

Two matching technologies for multimode waveguides were used for the microfabrication of vertical and horizontal waveguides. Wafer-level nanoimprinting technology creates highly precise horizontal waveguides with polymer (refractive index nC = 1.56 at 850nm) as core. The waveguide ends in a reflecting facet, created by nanoimprint lithography (i), aligned to the optical TSV. To carry out the imprint, first a Si etch structure is created using a special plasma etching process (combination of isotropic and anisotropic etching processes). A PDMS master is then created from this Si template. To achieve total internal reflection, 2μm SiO2 (nCl = 1.46) is used as clad to imitate step-index optical fiber structure. The vertical waveguide, i.e. TSV (diameter 20-40μm in 200-380 μm Interposer) is realized by specially developed Si-etching, oxidation and SU-8 filling techniques.

Dicing of waveguides is presented as a second technology to create a coupling element on a polymer waveguide (ii). The reflecting mirror is created by 45° angled groove with a V-shaped dicing blade. The dicing edge is aligned to the TSV to create a facet on the waveguide for 3D optical interconnect. Due to the difference of refractive indices between core and clad (SiO2 & air), the total internal reflection is observed. Losses caused by the surface roughness and the efforts to reduce them are investigated in this paper.

In order to demonstrate and characterize a 3D optical interconnect network, a measurement setup is implemented. In this, a set of Multiple-Fiber Push-On cables (MPO) are used to evaluate power losses of the reference setup and characterize the 3D optical link (comprising two vertical TSVs and horizontal optical interconnects integrated on a Si interposer). Thus, a combination of highly precise structuring technique enables fabrication of advanced 3D optical interconnects on silicon interposer, to facilitate the realization of the emerging technologies for the upcoming years.

10242-30, Session PS

Localized photonic nanojets formed by core-shell diffraction gratings

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Because of the diffraction limit, nano-scale targets cannot be observed directly by conventional microscope. In the past decade, the development of high-resolution optical microscopy techniques has become an important issue in the optical research fields. The nano-scale imaging techniques require the collection of objective information in the near field. The principal possibilities of such imaging include near-field probes, negative index metamaterials, hyper-lens and super-lens. These imaging techniques have not yielded extensive applications because of fabrication complexities, weak optical throughput, narrow spectral bandwidth, and high cost. Recently, the super-resolution imaging is introduced by using dielectric microcylinders and microspheres. The super-resolution capability of such microcylinders and microspheres is proposed to stem from their extreme sharp focusing characteristics. This physical phenomenon named photonic nanojet. Microcylinders and microspheres should be positioned closer to the observed surface compared to solid immersion lens since they have smaller contact spaces. In practice, the operation of localized photonic nanojet generated by microspheres is a challenging task because the management and fixation of isolated microspheres on the sampling object have some technical difficulties.

From the viewpoint of physical optics, the microsphere array can be deemed as a phase plate with periodic alteration of refractive index. Instead of microsphere array, we consider the problem of diffraction grating for the generation of photonic nanojet. The generations of localized photonic nanojets using core-shell diffraction gratings working in the visible light region are demonstrated numerically. The power flow patterns for the core-shell diffraction gratings are simulated by using the finite-difference time-domain method. The focusing qualities of localized photonic nanojets are evaluated in terms of focal length and transversal width along propagation and transversal directions. We construct three-dimensional finite-difference time-domain computational model for core-shell diffraction gratings. Considering the photonic nanojet formation from core-shell diffraction gratings, the metallic shell is proposed to enhance the intensity of photonic nanojet. The refractive indices of the dielectric diffraction grating and surrounding medium are 1.5 and 1. The refractive index of the gold shell is 1.46+1.954i. A monochromatic radiation with wavelength 532 nm propagates from the bottom boundary of the model. The high-intensity photonic nanojet with subwavelength focusing is obtained from core-shell diffraction gratings. The core-shell diffraction gratings could be functional for the super-resolution large-area imaging technique for nano-scale targets.

10242-31, Session PS

Determination of refractive index of submicron-thick films using resonance shift in a four-layer slab waveguide

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The measurement of refractive index of very thin films at the order of ten to hundred nanometers is cumbersome and usually requires employing sophisticated techniques such as the spectral ellipsometry. In this presentation we demonstrate a very simple contact method for measuring the refractive index of thin films. In the method a three-layer slab waveguide with known resonance conditions – the effective refractive indexes of the modes – is used as a substrate for the measurement. As the material under investigation is added on to the substrate, the resonance mode locations vary. The variation can be approximated according to the four-layer slab waveguide model, however it requires knowing the thickness of the added layer. Simple analytic transcendental equations should be solved for the calculation of effective refractive indexes of a four-layer slab waveguide.

In our experiments we used the prism-coupling technique for exciting the guiding modes in our samples. In this technique the sample is in a

mechanical contact with a high refractive index prism at the coupling point. Through the coupling point the light is coupled into the planar waveguide at specific resonance angles which are directly related to effective refractive indexes of the sample. For determination of refractive index of thin films we capture the resonance condition as a function of layer thickness. We used indium-tin-oxide (ITO) layer on glass as the substrate and polysulphone (PSU) with known refractive index as the material for testing the method. In the presentation we will provide the theoretical background of the method, demonstrate the experimental results obtained during the implementation of the technique as well as discuss its main strengths and flaws.

10242-32, Session PS

Small-signal analysis of ultrahigh speed 30 GHz VCSELs using an advanced multimode approach

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In recent years, vertical-cavity surface-emitting lasers (VCSELs) have emerged as a pioneering solution for many high-speed data communication challenges like optical interconnects. Furthermore, VCSELs with direct modulation are increasingly playing an important role in today's standardized serial data rates. Therefore, higher bandwidth optical interconnects with data rates in the range of 100 Gbit/s require directly modulated VCSELs with ultimate speed ratings. Intensive research, along with deeper understanding of the VCSELs physics and dynamics, led to further improvements in the modulation performance of these lasers in a direction greater than 30 GHz bandwidth.

The small-signal analysis was done on our next generation VCSEL devices, an optimized version of our high-speed, temperature-stable 980 nm VCSELs. Sharing the very short half-lambda cavity and a binary bottom-mirror with 32 pairs, the epitaxial layers are further optimized in order to minimize internal losses. Like in the previous VCSEL devices, parasitics are controlled by two oxide apertures and highly conducting current-spreading layers. InGaAs multiple quantum well active layers with strain compensated GaAsP barriers were utilized for getting a high differential gain. The 22-pair Al12Ga88As/Al90Ga10As top-mirror was replaced by an 18-pair GaAs/Al90Ga10As mirror to decrease photon lifetime, improve confinement and heat extraction. The epi-structure was fabricated by IQE Europe and the development of a new structure with a high-contrast-grating mirror is in process.

Compared to large-signal analysis, the small-signal modulation response of a VCSEL can be isolated from the entire system, thus providing accurate information on the intrinsic laser dynamics. Until now, it was assumed that the dynamic behavior of oxide-confined multi-mode VCSELs can be modeled using the single-mode rate equations developed for edge-emitters, even though the deviation between the single-mode based model and the measured data is substantially large. Using an advanced multi-mode small-signal modulation approach, we analyzed the small-signal modulation response and proved that the dynamic behavior of multi-mode VCSELs can indeed be modeled by the single-mode rate equations, if the lasing modes share a common carrier reservoir. However, the shared carrier reservoirs in ultra-high performing VCSELs driven at high currents tend to split up among the resonating modes, making the single-mode modulation approach fail to model the small-signal modulation behavior of these VCSELs.

In this work, detailed small-signal analysis of VCSELs is performed based on an advanced multi-mode rate equations model. The analyzed devices showed modulation bandwidth exceeding 30 GHz. The measured data was fitted to both, single-mode and multi-mode rate-equations, and it was assumed that the self-organized carrier reservoirs are formed due to spatial hole burning. It was found that the fitting to the theoretically developed multi-mode model is by far better than the single-mode one. The common set of figures of merit is extended consistently to explain dynamic properties caused by carrier fluctuations. Furthermore, besides damping and relaxation oscillation frequency, the advanced model can reveal information on the photon lifetime and highlight high-speed effects such as reduced damping in VCSELs due to negative gain compression factor.

10242-33, Session PS

High transmittance and broaden bandwidth through the morphology of antirelfective layers on THz polarizer with Si substrate

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Anti-reflection coating required precise thickness of a quarter of wavelength and refractive index of square root of Si refractive index for a single frequency with high transmittance. Hence, we etched cylinder holes on the surface of Si to tune to a quarter of wavelength as a way to construct AR layer with specific index and also specific thickness. After the fabrication of AR layers, the Cu wire-grid gratings and low temperature In/Sn solder sealed rings were patterned on the other side of the respective Si wafers. Two silicon wafers were bonded together, AR coating is outward and gratings are inward, to prevent Cu corrosion. Furthermore, broaden bandwidth of transmittance spectrum would be approached by stacking different central frequency AR layers or using different etching profile with non-columnar structure. Finally, THz time-domain spectroscopy (TDS) was used to measure the polarizers. The central frequency of AR layer ranged from 0.5THz to 2THz depending on the etching depth with an approximate bandwidth of 0.5THz. The power transmittance is closed to 100% at central frequency and the extinction ratios of TE to TM incident waves are around 30dB depending on the pitch of Cu wires. The transmittance spectrum is widened and has a nearly uniform transmittance exceeding 70% in bandwidth by bonding two different central frequency AR layers or gradient index caused by non-columnar etching profile.

10242-34, Session PS

The behavior of the geometrical parameters of optical beam of optical passive components in the thermal load

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Conventional lines and cables are slowly being replaced by fiber optic and conventional integrated circuits they are being replaced with optical integrated circuits. After years of expansion of new fiber networks, there are new issues that in constructing nobody bothered with. When asked about accelerated aging of passive optical elements, we can be looked at the issue from several angles. The paper discuss about aging of the passive optical couplers and the passive optical splitters in their burdened high temperature. The article focus on applied research and experimental development of resources for safety operation of optical networks in environment with higher temperature. It addresses issues of accelerated ageing of optical fiber components in their burdened with high temperature. How does temperature influence on optical network elements? It is necessary to specify the changes in the optical coupler and find out why these changes occur. This article is devoted experimental measurement of the impact of temperature loading on the geometrical parameters of optical beam of SM optical FBT couplers. In the paper there are compared couplers of different manufacturers and different dividing ratios of output power. Optical passive component were continuously exposed to temperature 95°C for long time period. Measurements are focused on the parameters of geometry of optical beam. Graphical and mathematical detect changes in the dissemination of energy coupler after long lasting dose of temperature loading are useful to understand the phenomenon of accelerated aging elements of optical networks in environments with an higher temperature.

10242-35, Session PS

Design of silicon electro-optic modulator based on the epsilon-near-zero effect of graphene

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Graphene, a monolayer of carbon atoms in a hexagonal lattice, has recently gathered much attention because of its extra-ordinary optoelectronic properties and high CMOS compatibility. To date, rigorous experimental and theoretical investigations on graphene-based silicon optical modulators have been performed because silicon optical modulators are essential components, interconnecting the electric world and photonic regime. In this paper, we theoretically investigated the optical characteristics of the graphene-based silicon electro-optic modulator, considering the isotropic and anisotropic graphene models. In the anisotropic graphene model, the light absorption by graphene is based on the Pauli blocking principle, while graphene's epsilon-near-zero effect is dominant in the optical power modulation under the isotropic graphene model.

In the isotropic graphene model, an abrupt decrease of the transmission is observed at approximately μc = 0.5 eV, which conserves the epsilon-near-zero (ENZ) effect of graphene. When μc is approximately 0.5 eV, the real part of graphene's permittivity reaches nearly zero at a 1.55 ?m wavelength. The field amplitude at the graphene–hBN interface is maximal. At the same time, a nonzero imaginary part of graphene's permittivity causes the field to undergo high absorption of the optical power of the guided-mode. As a result, the transmission is highly attenuated. The ENZ effect of graphene becomes more significant as the thickness of hBN layer (ThBN) increases. In the anisotropic graphene model, photons are absorbed by graphene if $\mu c < 0.3$ eV, while they are not absorbed by graphene if $\mu c < 0.5$ eV, due to the Pauli blocking principle.

Based on the simulation data on the graphene-integrated silicon optical modulator, we carefully confirmed that graphene could be treated as an isotropic material and that graphene has the epsilon-near-zero (ENZ) effect, which shows an abrupt loss that increases around its ENZ region.

10242-37, Session PS

Self-assemble organic molecular micron-sized tubular structures for active and passive waveguiding regimes

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Organic optical waveguides made from small molecules can break the limitations such as, refractive index or ease of creating cross-junctions between wave guiding of presently available inorganic commercial materials, which, are predominately applied in design of photonic integration devices, e.g. SiO. Alternate photonic materials include 1D self-assemble organic molecular waveguides which shows more decent features such as greater oscillatory strength of organic molecules and greater longitudinal-transverse exciton splitting energy. Here we study self-assembled of 9-diethylamino-5-benzo[?]phenoxazinone 9 (Nile Red). AFM, SEM, Raman imaging, FLIM, and anisotropy studies demonstrate that such materials form micron-sized tub-like structures with rectangular shape with nanosized opening with a size comparable with the applied optical wavelengths. Studying both active and passive wave guiding modes was undertaken. Applying wavelengths in resonance (470, 532, and 632.8nm) and in non-resonance (785nm) with the molecular electronic absorption bands was undertaken for active and passive wave guiding studies. PL spectra and lifetime at the laser capping point, the body and emerging light points were investigated. Meanwhile, Raman scattered photons were also acquired which maintain the polarised light propagation direction(s) and its interaction with tube molecules. Studies of single and interacting tube junctions has been performed. These studies showing that excellent wave guiding features are present using these self-assembled micron-tube structures.

10242-39, Session PS

Experimental analysis of silicon oxycarbide thin films and waveguides

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Silicon oxycarbide (SiOC) has evolved as an interesting material in scientific community for its excellent physical, mechanical, band gap and chemical properties that can be tailored through variation in composition. It has been adopted as an anode material for Li-ion batteries, low dielectric material for interlayer dielectrics, and its photoluminescence and electroluminescence properties have been exploited. Thin films of SiOC are typically realized using CVD and sol-gel pyrolysis techniques under various pre- and post-deposition conditions.

In this work we investigate the properties of SiOC thin films and optical waveguides prepared by rf reactive magnetron sputtering from a 99.99% pure silicon carbide (SiC) target at different rf power levels. SiOC depositions were performed on Si (100) substrates in a controlled ambient of argon and oxygen gases for a time of fifteen minutes. The thickness of SiOC layers deposited as a function of rf power (50 to 450 W) was measured to be 100 to 2200 nm with profilometer, respectively.

The SiOC films were fully characterized by spectroscopic ellipsometry over the wavelength range between 300 and 1600 nm. A model taking into account SiOC surface roughness and native SiO2 at the SiOC/Si interface was used to fit the ellipsometric data. To achieve Kramers-Kronig consistency in the optical constants, SiOC layers were represented by Tauc-Lorentz oscillator [1]. The optical band gap Eg of the SiOC films was seen to decrease from 3.5 to 2.75 eV when the rf power level is increased from 300 to 450 W. The dispersion curves of the SiOC optical constants (n,k) exhibit a smooth decreasing trend from UV through visible to near-IR regions. High transparency in both visible and near-IR regions was observed, the extinction coefficient being less than 10-5. By increasing the rf power, the refractive index of the SiOC films increases from 1.4 to 1.85 at wavelength around 1550 nm, and increases from 1.4132 to 1.9210 at 633 nm. Good agreement with refractive index measurements performed with prism-coupling method was found. Results suggest that the variation in refractive index as a function of rf power is due to change in carbon content of SiOC films, since at higher power more SiC is sputtered and eventually more carbon is incorporated in the films. Further the rms roughness measured as a function of increasing rf power by AFM was found between 0.3 and 2.5 nm. Low roughness, low material absorption and tunable refractive index make SiOC a promising candidate for integrated-photonics. The optical waveguides have been fabricated in SiOC (n=1.7) which gives high index contrast of 17.2 %. Rib and channel waveguides buried in PECVD silica (n=1.45) are realized with photolithography and reactive ion etching techniques. SEM analysis of waveguides shows good quality rectangular profile and the width of waveguides varies between 1.8 and 4 um. The waveguides in SiOC are under characterization and good results are expected which will be presented in the conference.

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Conference 10243: X-Ray Lasers and Coherent X-Ray Sources: Development and Applications

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Part of Proceedings of SPIE Vol. 10243 X-ray Lasers and Coherent X-ray Sources: Development and Applications

10243-1, Session 1

Progress on ultra-intense soft X-ray lasers *(Invited Paper)*

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We report here recent work on an optical-field ionized (OFI), high-order harmonic-seeded EUV laser. The amplifying medium is a plasma of nickel-like krypton obtained by optical field ionization focusing a 1 J, 30 fs, circularly- polarized, infrared pulse into a krypton-filled gas cell or krypton gas jet. The lasing transition is the 3d94p (J=0) ?? 3d94p (J=1) transition of Ni-like krypton ions at 32.8 nm and is pumped by collisions with hot electrons.

The polarization of the HH-seeded EUV laser beam was studied using an analyzer composed of three grazing incidence EUV multilayer mirrors able to spin under vacuum. For linear polarization, the Malus law has been recovered while in the case of a circularly-polarized seed, the EUV signal is insensitive to the rotation of the analyzer, bearing testimony to circularly polarized.

The gain dynamics was probed by seeding the amplifier with a high-order harmonic pulse at different delays. The gain duration monotonically decreased from 7 ps to an unprecedented shortness of 450 fs FWHM as the amplification peak rose from 150 to 1,200 with an increase of the plasma density from 3 ? 1018 cm?3 up to 1.2 ? 1020 cm?3. The integrated energy of the EUV laser pulse was also measured, and found to be around 2 ?J. It is to be noted that in the ASE mode, longer amplifiers were achieved (up to 3 cm), yielding EUV outputs up to 14 ?J.

10243-2, Session 1

DAGON: a ·3D Maxwell-Bloch code

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High Order Harmonics (HOH) are a powerful tool to unveil the inner dynamics of plasmas. When propagating through a plasma, HOH may suffer refraction, attenuation and even amplification if a population inversion in an atomic transition matching the HOH wavelength is created in the plasma. Thus, HOH allow to probe physical quantities as the electron density or the gain recovery time. However, most plasmas are spatially and temporally inhomogeneous. While 1D simulations, properly homogenized, can be used to model the propagation of HOH, full time-dependent 3D codes are needed to probe the full 3D structure of the plasma. DAGON is a 3D time-dependent Maxwell-Bloch code developed at the Instituto de Fusión Nuclear. It is coupled to hydrodynamic and atomic physics packages to model the evolution of the plasma during the propagation. With this code we can model processes like the amplification of spontaneous emission in atmospheric nitrogen, the dynamics of Rabi oscillations in inhomogeneous plasmas and the amplification of ultra short pulses via collisional ionization gating.

10243-3, Session 1

Highly coherent lab-scale soft x-ray laser using multistage amplifier

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The development of high-brightness soft x-ray laser (SXL) at the laboratory scale is of great interest for numerous applications. Conventional plasma x-ray lasers have the characteristics of high spatial coherence, while less temporal one. To realize a fully coherent SXL, we proposed the use of an injection seeding technique, in which high-order harmonic pulses are injected into multi-stage amplifier. In this scheme, an x-ray parametric amplifier is used to improve the spatial coherence and reduced the beam divergence, while a transient collisional excitation plasma is employed for power amplification. Therefore, intense soft x-ray pulses can be generated with extremely high coherence, low divergence, shot pulsewidth and defined polarization. A table-top Ti:Sapphire laser with a repetition rate of 10 Hz is constructed as the laser driver of the XRL system. The central wavelength of the Ti: Sapphire laser is tuned at 792.3 nm, by which the lasing transition at 13.9 nm in Ni-like silver matches the wavelength of 57th order harmonics. The high-order harmonics generated in neon gas are further amplified due to high-order parametric interaction in helium gas. In this report, we show the development status and preliminary results of the XRL.

10243-4, Session 1

Laser-driven coherent sources of short-wavelength radiation at PALS and ELI Beamlines *(Invited Paper)*

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We present recent activities at PALS research centre dedicated to development of short-wavelength radiation sources through various processes using a 20TW Ti:sapphire laser. There are two types of sources of coherent XUV radiation being developed here: high-order harmonic generation (HHG) from various gaseous targets and collisionally pumped soft X-ray laser from slab targets. Also the plans for the implementation of a high-order harmonic beamline employing 1 kHz 100 mJ 20 fs laser system at upcoming ELI Beamlines facility are discussed.

At PALS we have tested different experimental setups for HHG in gas cells of various lengths in order to obtain the scaling of XUV beam parameters on the f-number of the focusing optics. Three focusing geometries employing different number of laser amplifiers were tested, short one (f = 0.3-0.75 m) with 1 kHz rep. rate and pulse energy ~0.5 mJ and long ones (f = 2 m and f= 5 m) with 10 Hz repetition rate. The scaling of the HHG pulse energy and the beam divergence of the generated radiation on the f-number of the driver at optimum phase-matching conditions (cell length, density of the gas, position of the focus) was assessed. As predicted by the theoretical works, the efficiency of the generation under these conditions does not scale with f-number, i.e. with the energy of the driving laser pulses.

Employing more powerful laser, which should be soon available at ELI Beamlines facility near Prague, we suppose to scale-up the average power generated by HHG by few orders of magnitude. Plans for the implementation of a HHG beamline driven by 1 kHz 100 mJ 20 fs laser system will be shown.

Further we have demonstrated lasing of Ni-like Mo (lambda = 18.9 nm) using pulses of Ti:sapphire laser chain with pulse energy up to 500mJ on a slab target. A suitable amplifying medium has been created by a single shaped laser pulse containing a long prepulse with duration 4 – 5 ns that created a plasma column which was consequently heated by a short ~ps pulse to produce transient population inversion. The experiment has been performed for pumping incidence angles ? = 20˚ and ? = 25˚ obtaining small signal gains of G = 29.3 cm-1 and G = 38.3 cm-1 with gain-length products 12.6 and 13.4, respectively. Further we focused on the speckle statistics of the far-field intensity profiles of this XRL, from which we were able to obtain number of longitudinal modes and comparing to calculated coherence time using simple 1D radiation transfer code we could estimate the XUV pulse duration.

10243-5, Session 2

High-spatial-resolution X-ray bio imaging with liquid-metal-jet sources *(Invited Paper)*

Hans M. Hertz, KTH Royal Institute of Technology (Sweden)

2D and 3D X-ray imaging in of small animals and their organs is an essential tool biomedical research. High spatial resolution is of key importance, both in classical absorption imaging and in more recent phase-contrast imaging. However, for laboratory imaging systems the limited brightness of the classical microfocus x-ray source typically constraints the imaging quality, either in resolution or exposure time. We have introduced a regenerative anode (liquid-metal-jet) that allows operation of x-ray microfocus sources at electron-beam power densities orders of magnitude higher than classical tubes. Present systems typically rely on room-temperature liquid-metal alloys and operate with a 4-20 mm spot size in the 10-160 kV range with one order of magnitude higher brightness than state-of-the-art x-ray micro-focus tubes. We use liquid-metal-jet sources in magnifying x-ray imaging schemes, for high-spatial resolution studies of whole animals (mouse, zebrafish), organs (lungs, muscles) and vasculature (kidney, ear, tumors). Typically we employ propagation-based phase contrast and combine with tomographic reconstructions for 3D imaging. The method allows observation down to cellular, and in some cases subcellular, detail within the context of the whole organ or animal.

10243-6, Session 2

Thomson laser-electron x-ray source: towards k-edge millisecond coronary angiography

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An idea to apply laser electron X-ray sources (LEXS) technology in medicine [1,2] is a driving force for a number of efforts and projects [3-6]. Cardiac catheterization (CC) – the leading method for visualization of insides of coronary arteries since 1986 – is a challenge for an application and development of advanced X-ray sources [7,8]. The LEXS offers a new approach to the CC problem due to a well-collimated beam and a reasonably narrow spectral band of X-rays. An analysis of a contrast to noise ratio (CNR) for a monochromatic source shows that the optimal X-ray photon energy for imaging of human coronary vessels lies in the vicinity of the photo-absorption K-edge of a contrast agent. This conclusion is supported by the results of clinical tests of 45 patients made by coronary computed tomography systems with variable tube voltages in a range from 70 to 100 kV [9]. Corresponding parameters of the LEXS systems capable of delivering required exposure dose in 1 millisecond are found and discussed following the approach reported in [10].

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10243-7, Session 2

Single shot NEXAFS spectroscopy using a soft X-ray laser-produced plasma source

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Near edge X-ray absorption fine structure (NEXAFS) spectroscopy is a powerful characterization tool which enables the investigation of the local geometry of a probed atom, yielding information on the oxidation state, inter-atomic distances or bond angles. The main constituents of biological specimen can only be probed with soft X-ray radiation (K edges of C, N, O), thus, confining measurements to large scale facilities as robust soft X-ray laboratory sources are still not readily available.

To overcome this obstacle, we have developed a stable, highly brilliant laser-produced plasma (LPP) source for the soft X-ray range. With a newly developed reflection zone plate (RZP) spectrometer, high resolution NEXAFS measurements at the carbon and nitrogen K-edge (E/?E ~ 950) are feasible within one single shot (1.2 ns). While the spectrometer is adapted to our specific laboratory source, the concept is easily transferrable to other point-like sources.

Single shot NEXAFS measurements minimize the radiation dose and thus possible damage inflicted on a sample. Therefore, monitoring of possible degradation of radiation sensitive samples is rendered feasible, as well as efficient time-resolved and/or pump-probe measurements.

Within an optimization of the setup the emission spectra of seven different target materials (Kapton, Cu, Pd, Sn, Ta, W and Au) were investigated using a flat-field spectrometer. This calibrated, compact spectrometer utilizes two variable line-spaced gratings, covering energies between 60 eV and 1200 eV (1 - 20 nm). The main goal of these measurements was to find the most suited target material for NEXAFS measurements at the two absorption edges. For comparison, we present single shot NEXAFS measurements of a thin Polyimide-foil (112.5 nm) performed with different target materials. As an outlook measurements on thin films of bio-molecules produced with different preparation methods will show the potential for lab-based pump-probe experiments.

10243-8, Session 2

Soft X-ray nanoscale imaging using highly brilliant laboratory sources and new detector concepts *(Invited Paper)*

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Laboratory based laser driven short pulse x-ray sources like laser produced plasmas (LPP), high harmonic generation (HHG) and plasma based X-ray lasers (XRL) exhibit a great potential for imaging and spectroscopy in the soft x-ray range. These sources are complementary to large scale facilities like synchrotrons or free electron lasers. LPP as well as XRL and HHG sources have been already successfully applied in nanoscale imaging in both life and material sciences. However, only few examples of high resolution three dimensional nanoscale images recorded with these sources exist. This is due to limited (in comparison with synchrotron sources) average photon flux and the lack of efficient X-ray optics. This limitation can be overcome using high repetition rate (1 kHz and higher) pump lasers.

However, optimization potential for soft X-ray imaging is not exclusively based on the flux of the photon source but also on efficient detection with high spatial resolution. Commercially available cooled back-illuminated CCD cameras which are widely used as detectors in soft X-ray imaging exhibit a relatively large pixel size of 13 mkm or larger limiting in some cases the spatial resolution. This is particularly the case in zone plate X-ray microscopy at moderate magnifications and in new imaging schemes such like coherent diffraction imaging (CDI) or Fourier transform holography. Sub-pixel displacements of detectors combined with appropriate image reconstruction algorithms hold the promise for enhanced spatial resolution beyond the pixel limit. Such a super resolution technique has been already demonstrated in consumer camera electronics in the visible range but until now not in the soft x-ray range using scientific grade large area CCD detectors.

In this contribution, we report about nanoscale imaging using a LPP based laboratory transmission X-ray microscope (LTXM) in the water window operating @ 500 eV. The highly brilliant soft X-ray radiation of the LTXM is provided by a LPP source pumped by a high repetition rate laser. A multilayer condenser mirror focuses the radiation to the sample. An objective zone plate maps the magnified image of the sample on the super resolution detector. This novel scientific super resolution camera employs a deep cooled soft-X-ray CCD imaging sensor sandwiched with an xy piezo stage to allow subpixel displacements of the detector. The camera is read out using a very low noise electronics platform, also directing low µm shifts of the sensor between subsequent image acquisitions. Finally an algorithm computes a high resolution image from the individual shifted low-res image frames.

To demonstrate the sub-pixel resolution of the detector the magnification of the LTXM has been chosen such that the spatial resolution was limited by the pixel size. Both resolution test charts and typical biological samples have been investigated in this configuration. Evaluating these data we will discuss the interplay between optimum resolution, magnification and recording time.

In the conclusion we will discuss the application of the new detector in microscopy using "tender" X-rays with photon energies up to 2 keV and in CDI using HHG and XRL.

10243-9, Session 3

Development of ultrashort x-ray/gamma-ray sources using ultrahigh power lasers *(Invited Paper)*

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Short-pulse x-ray/gamma-ray sources have become indispensable light sources for investigating material science, bio technology, and photo-nuclear physics. In past decades, rapid advancement of high intensity laser technology led extensive progresses in the field of radiation sources based on laser-plasma interactions - x-ray lasers, betatron radiation and Compton gamma-rays. Ever since the installation of a 100-TW laser in 2006, we have pursued the development of ultrashort x-ray/gamma-ray radiations, such as x-ray lasers, relativistic high-order harmonics, betatron radiation and all-optical Compton gamma-rays. With the construction of two PW Ti:Sapphire laser beamlines having peak powers of 1.0 PW and 1.5 PW in 2010 and 2012, respectively [1], we have investigated the generation of multi-GeV electron beams [2] and MeV betatron radiations. We plan to carry out the Compton backscattering to generate MeV gamma-rays from the interaction of a GeV electron beam and a PW laser beam. Here, we present the recent progress in the development of ultrashort x-ray/gamma-ray radiation sources based on laser plasma interactions and the plan for developing Compton gamma-ray sources driven by the PW lasers. In addition, we will present the applications of laser-plasma x-ray lasers to x-ray holography and coherent diffraction imaging.

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10243-10, Session 3

Generation of intense attosecond soft x-ray pulses by IR-field dressed x-ray lasers

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At present, the only source of attosecond pulses suitable for study and control over the ultrafast intra-atomic dynamics is high-order harmonic generation of laser radiation in gases [1]. This method allows producing intense sub-femtosecond pulses of extreme-ultraviolet (XUV) radiation, but in soft x-ray spectral range and especially in a "water window" (2.3–4.4 nm) its efficiency is still rather limited. On the other hand, high energy (up to several mJ) picosecond pulses of XUV or soft x-ray field can be produced by laser-plasma based x-ray lasers [2, 3]. At present, x-ray lasers find numerous applications in microscopy, micro-holography and nano-lithography; however they cannot be used for study of sub-ps dynamical processes.

Recently, we proposed to form trains of sub-femtosecond pulses based on modulation of active medium of x-ray lasers by a moderately strong infrared (IR) laser field [4]. The pulse formation relies on spectral broadening of resonant response of generating ions to the XUV/x-ray field under action of the IR radiation [5, 6]. In the present contribution, we further extend this study and show a possibility to produce trains of high-energy attosecond pulses either via modulation of active medium of an x-ray laser, or via transformation of XUV/x-ray field in a resonant absorber dressed by IR laser field. In the former case, XUV/x-ray field can be amplified in modulated medium by two orders of magnitude, while in the latter case the efficiency of pulse formation can exceed 80%. Besides, we have shown the possibility to amplify a high-harmonic signal in a modulated active medium of x-ray laser, thus producing a train of nearly bandwidth-limited sub-femtosecond pulses without need for compensation of attochirp.

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10243-11, Session 3

Using the XFEL to drive gain in L-shell systems using photoionization processes

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Many photo-pumped X-ray laser schemes have been proposed but demonstrating these schemes has proved to be elusive because of the difficulty of finding a strong resonant pump line or X-ray source. With the availability of the X-ray free electron lasers (X-FEL) a tunable X-ray laser source can be used to replace the pump line or X-ray source in previously proposed laser schemes and allow researchers to study the physics and feasibility of photo-pumped laser schemes.

Five years ago an inner-shell X-ray laser was demonstrated at 849 eV in singly ionized neon using the X-FEL at 960 eV to photo-ionize the 1s electron in neutral neon followed by lasing on the 2p – 1s transition in singly-ionized neon. It required a very strong X-ray source that could photo-ionize the 1s (K-sehll) electron on a time scale comparable to the intrinsic auger lifetime of 2 fsec.

We extend this work from K-shell to L-shell transitions. We show how the XFEL could be used photo-ionize L-shell electrons to drive gain on n=3-2 transitions in singly-ionized Ar and Cu plasmas. For Ar this requires an XFEL near 350 eV with lasing on 3-2 lines at 220 and 310 eV. The Cu scheme requires an XFEL above 950 eV with lasing on 3d-2p lines at 928 and 948 eV.

10243-12, Session 3

Amplified spontaneous and stimulated Mg L emissions from MgO pumped by FEL pulses

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A MgO solid target has been irradiated by 65 fs/56.8 eV XFEL single pulses delivered by the EIS-TIMEX beamline at the FERMI@Elettra facility operating in FEL-1 mode. The EUV radiation emitted in the Mg L2,3 spectral range has been recorded by an avalanche photodiode APD with a 1 mm wide slit positioned at 120 mm away from the sample on a circular rotating ring; a [Al 40 nm/Mg 0.8 ?m/Al 40 nm] filter is placed in front of the APD to reject the long wavelength radiations (visible, seeding laser) and the FEL exciting radiation but allowing transmission of the Mg L emission with a rejection rate of 5 x 104. The emitted radiation intensity has been measured versus the take-off angle ? at the maximum available XFEL pump intensity, that is 6 10^14 W/cm-2; this angular distribution presents a maximum around 52° and some oscillations. This maximum corresponds to a privileged direction given by the balance between the absorption length of the pumping radiation and the interaction length of the emitted stimulated radiation, as previously observed and interpreted by Beye et al. for a silicon target [1]. The emitted radiation intensity has been also recorded versus the XFEL pump intensity with the detector located in the privileged emission direction (?=52°)?. One observes as the pump intensity grows, first a slowly increasing plateau up to a threshold value about 7 x 10^12 FEL photons/shot (4.3 x 10^14 W cm-2) and then a large enhancement from this threshold value. This behaviour is typical of the travelling wave ASE with a clamping of the gain at the pumping threshold for the stimulated emission. This behaviour was reported by Yoneda et al. [2] with a copper target in transmission geometry. Calculations performed with a hydrodynamical code indicate that the electron temperature of the sample is close to 10 eV, which means that the sample is then in a dense plasma state.

A phenomenological model based on rate and transport coupled equations including the physical state of the target has been developed to account for the experimental results. The theory reproduces both the angular distribution and the evolution of the emitted intensity as a function the pump intensity. Thus the experimental pumping threshold value is a fair agreement with the theoretical value that is 5.14 x 10^14 W cm-2. As a summary, it has been observed for the first time, EUV stimulated emission pumped by XFEL pulses from an initially solid target, formed in the regime of travelling-wave ASE in backward geometry.

[1] M. Beye et al. Nature 501, 191 (2013).

[2] H. Yoneda et al. Nature 524, 446 (2015).

10243-13, Session 3

Prospects of quantum X-ray lasers pumped by X-ray free electron lasers

Karol A. Janulewicz, Institute of Optoelectronics, Military University of Technology (Poland)

A few years ago, the innershell puming scheme suggested by Dugay&Rentzepis in 1967 has been realized and the puzzle of its resistance to demonstrational effort has been solved. The classical broadband pumping by incoherent sources appeared deadly to the kinetics of the involved levels. The narrowband XFEL proved to be the only reliable pumping source. The first photoionized innershell XRL used gas and it is natural that the question about the solid target arises. Very recently the relevant experiment at LCLS proved that the scheme based on direct irradiation of a metal foil is also viable [1]. The photon flux has been amplified by about six orders of magnitude and the saturation achieved proved irrefutably that it is really lasing. Here, we want to discuss some aspects of the scheme future in the terms common for the classic plasma-based X-ray lasers. The problem of geometry of the interaction area, coupling of the involved levels together with some specific features of the levels kinetics (Auger process) and their influence on the output parameters as coherence and polarization will be discussed in detail. It will be attempted to give answer what is the pumping threshold for obtaining such a lasing and the same to define energetic needs and demands for focusing parameters for the pumping radiation. Discussion of the amplification process dynamics in such a scheme will be addressed as well.

[1] U. Bergmann, private communication

10243-14, Session 4

High repetition rate and shorter wavelengths: progress in soft x-ray laser development and applications at Colorado State University *(Invited Paper)*

Jorge J. Rocca, Brendan A. Reagan, Yong Wang, Cory M. Baumgarten, Alex Rockwood, Shoujun Wang, Michael A. Pedicone, Mark Berrill, Vyacheslav N. Shlyaptsev, Chan Kyaw, Liang Yin, Hanchen Wang, Mario C. Marconi, Carmen S. Menoni, Colorado State Univ. (United States)

We will review recent progress in the development of high repetition, high average power rate soft x-ray lasers at 10-20 nm wavelength, and the compact diode- pumped solid state lasers that drive them. We will also report advances in the development of collisionally pumped soft x-ray lasers at sub-10 nm wavelengths. Results and prospects of the use of these lasers in applications will be discussed.

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10243-15, Session 4

Soft X-ray ablation mass spectrometry: enhanced mass range and sensitivity

Ilya Kuznetsov, Tyler Green, Colorado State Univ. (United States); Weilun Chao, Lawrence Berkeley National Lab. (United States); Andrew M. Duffin, Pacific Northwest National Lab. (United States); Jorge J. Rocca, Carmen S. Menoni, Colorado State Univ. (United States)

Laser ablation and ionization combined with mass spectrometry (MS) forms the basis of one of the most widely exploited analytical tools of the solid state. We have previously reported the first demonstration of soft X-ray laser (SXRL) ablation mass spectrometry using the focused 46.9 nm wavelength output from a compact capillary discharge laser. The focusing of the SXRL beam into 100 nm diameter spots, its high absorption in most materials and efficient photo-ionization contribute to the nanoscale spatial resolution and attomole sensitivity of the method. The high sensitivity and spatial resolution of SXRL time of flight (TOF) MS has enabled three dimensional nanoscale composition imaging of a single microorganism. However, due to the high photon energy (26.4 eV) photoionization is often accompanied by extensive fragmentation of analyte molecules. This leads to interferences in mass spectra which complicates analysis.

This presentation describes the implementation of post-ablation soft ionization that is aimed at selectively extracting molecular or atomic information from the most abundant neutrals in the SXRL-created plasma. Post-SXRL ablation ionization is implemented using either the 355 nm wavelength output from a frequency tripled Nd:YAG laser or the 9th harmonic (118 nm) obtained by upconversion of the 3rd harmonic in a Xe:Ar mixture. Focusing the vacuum ultraviolet (VUV) light into the sample region allows for softer ionization of intact neutral molecules. This happens because the photon energy of the VUV light is just above the ionization potential of many organic compounds of interest, such as Cholesterol. Even though this method of post-ablation ionization is quite established in mass spectrometry, its combination with SXRL provides increased imaging resolution, sensitivity and mass detection range in comparison with what is obtained using conventional lasers or ion sources.

10243-16, Session 4

Applications of an extreme ultraviolet capillary discharge laser

Gregory J. Tallents, Univ. of York (United Kingdom)

Targets irradiated by EUV and x-ray lasers are heated predominantly by direct photoionization. With photo-ionization as a dominant heating mechanism, lower temperature and higher particle density plasmas are produced. With all laser-produced plasmas, an expanding plume of plasma allows only absorption where the electron density drops below a critical value (?1021/?2 ?m2 cm?3, where ? is the laser wavelength in units of microns). By reducing the wavelength into the EUV to x-ray region, the critical electron density is greater than solid and the laser photon energy Ep becomes sufficient to directly photo-ionize elemental components (ionization energy Ei), transferring energy (Ep ? Ei) to the ejected electron. As the critical electron density is higher than solid, the laser is able to penetrate any expanding plasma plume and heat solid material directly throughout the duration of a laser pulse with minimal formation of shocks consequent secondary target damage.

10243-17, Session 4

Tabletop two-color soft X-ray laser by means of Ni-like plasmas *(Invited Paper)*

Davide Bleiner, Leili Masoudnia, Mabel Ruiz-Lopez, Francesco Barbato, Yunieski Arbelo Pena, Andreas Borgschulte, EMPA (Switzerland)

Laser-produced Ni-like plasmas are proven active media for soft X-ray lasing in the home-lab, with the appealing potential to two-color lasing. The recent progress of user-lab sources, e.g. XFELs, has shifted the attention away from plasma technology, which however remains appealing for tabletop operation. Furthermore, two-color laser generation is very complex at accelerator facilities, relying on a number of alternative schemes discussed in the talk. In this work, two-color plasma-lasing at the transitions 3d94d1(J=0) --> 3d94p1(J=1) (collisional or monopole-pumping process) and the 3d94f1(J=1) --> 3d94d1(J=1) (photo- or dipole-pumping process) were studied experimentally and computationally.

Several key characteristics of collisional- and photo-pumping laser, such as divergence, pointing stability, and intensity were experimentally investigated. The measurements showed only slightly different pulse characteristics for the two lasing mechanisms, as affected by plasma inhomogeneity in temperature and density. Analytical expressions of these characteristics for both monopole and dipole-pumping were derived, and the computational analysis showed that the optimum plasma for the former is 20% hotter and 70% denser than the plasma that optimizes the latter lasing, although the former requires low opacity. The gain of monopole-pumping is 4 times higher than the gain for the dipole-pumping. The gain lifetime is a factor of 5 larger for the former, as well as the gain thickness that is a factor of 2 larger. It is also found that the gain build-up time for monopole and dipole-pumping are 0.7 ps and 0.9 ps, respectively, whereas the build-up length-scale is 11.5um and 6.3um, respectively.

This, along with the extremely narrow linewidth, opens new ways for advanced spectroscopy in the home-lab, such as X-ray absorption microscopy on a Li K-edge (Li imaging is relevant in battery research), which is discussed in the talk. Traditionally, such advanced spectroscopy was restricted to user-labs, e.g. laser networks, accelerators, etc, with the drawbacks of beamtime restriction and discontinuous accessibility. This has made user-labs the place for pioneering and “proof-of-principle” research, but not for “enabling” application which require 24/7 access.

10243-18, Session JS1

X-ray absorption spectroscopy of warm dense matter with betatron x-ray radiation *(Invited Paper)*

Felicie Albert, Lawrence Livermore National Lab (United States)

Betatron x-ray radiation, driven by electrons from laser-wakefield acceleration, has unique properties to probe high energy density (HED) plasmas and warm dense matter. Betatron radiation is produced when relativistic electrons oscillate in the plasma wake of a laser pulse. Its properties are similar to those of synchrotron radiation, with a 1000 fold shorter pulse. This presentation will focus on the experimental challenges and results related to the development of betatron radiation for x-ray absorption spectroscopy of HED matter at large-scale laser facilities.

A detailed presentation of the source mechanisms and characteristics in the blowout regime of laser-wakefield acceleration will be followed by a description of recent experiments performed at the Linac Coherent Light Source (LCLS). At LCLS, we have recently commissioned the betatron x-ray source driven by the MEC short pulse laser (1 J, 40 fs). The source is used as a probe for investigating the X-ray absorption near edge structure (XANES) spectrum at the K- or L-edge of iron and silicon oxide driven to a warm dense matter state (temperature of a few eV and solid densities). The driver is either LCLS itself or an optical laser. These experiments demonstrate the capability to study the electron-ion equilibration mechanisms in warm dense matter with sub-picosecond resolution.

10243-19, Session JS1

Time-resolved X-ray spectroscopy for X-ray-induced phenomena

Antonio Picón, Argonne National Lab. (United States)

Fundamental molecular processes that underlie chemical reactivity and biological processes typically involve intramolecular dynamics consisting of nuclear motion and the flow of charge and energy across atomic sites. Examples include photosynthesis, electron transfer in biomolecules, and molecular fragmentation.

Molecular phenomena initiated by the absorption of an XUV/x-ray photon is one of the most challenging questions for the new generation of XUV/x-ray sources. New capabilities at accelerator-based and laser-based sources are continuously being developed, being possible to nowadays generate two-color XUV/x-ray pulses with controlled time delay. The site-specificity of those photons allow the excitation of inner-shell electrons in a particular site of the molecule and, with a controlled time delay, the probing of the induced intramolecular dynamics in another site of the same molecule, opening the door to the unexplored field of intramolecular processes initiated by short-wavelength photons. Also, novel XUV/x-ray sources allow the generation of two-color pulses with a high spatio-temporal degree of coherence, suitable for quantum control schemes involving inner-shell electrons. In this talk, we present new theoretical and experimental results towards this direction [1,2,3] and discuss the promising perspectives of this exciting field.

[1] A. Picón et al., “Hetero-site-specific x-ray pump-probe spectroscopy for femtosecond intramolecular dynamics”, Nat. Commun. 7:11652 (2016)

[2] C.S. Lehmann et al., “Ultrafast x-ray-induced nuclear dynamics in diatomic molecules using femtosecond x-ray-pump – x-ray-probe spectroscopy”, Phys. Rev. A 94, 013426 (2016)

[3] A. Picón et al., “Stimulated Raman adiabatic passage with two-color x-ray pulses”, New J. Phys. 17, 083038 (2015).

10243-20, Session JS1

The EIS beamline at the seeded free-electron laser FERMI

Alberto Simoncig, Riccardo Mincigrucci, Emiliano Principi, Filippo Bencivenga, Laura Foglia, Andrea Calvi, Claudio Masciovecchio, Gabor Kurdi, Elettra-Sincrotrone Trieste S.C.p.A. (Italy); Alessia Matruglio, Simone Dal Zilio, Valentina Masciotti, Istituto Officina dei Materiali (Italy)

The Italian free-electron laser (FERMI) is currently the only fourth generation light source able to operate in the high-gain harmonic generation (HGHG) seeding mode, delivering XUV radiation characterized by a quasi transform-limited pulse structure, full control of the polarization and supreme transversal and longitudinal coherences. Its unique characteristics have recently opened the doors to a new class of time-resolved experiments, extremely difficult to be performed using self-amplified spontaneous emission FELs. Among the three currently operating beamlines, the Elastic and Inelastic Scattering (EIS) one has been designed for offering a wide range of experimental approaches to study the non-equilibrium dynamics of solids [1]. The EIS beamline is equipped with two end-stations, designed for exploring the potential of four-wave mixing spectroscopies in the XUV spectral range (TIMER) or the states of matter in metastable and extreme conditions (TIMEX), respectively [2-4]. Here we will report some of our most recent achievements, focusing on the recent time-resolved experiments performed at the TIMEX end-station on magnetic materials. The combination of XUV pulses and optical laser ones, have allowed us to perform a novel study of the transient magnetization of the antiferromagnetic nickel oxide (NiO), pumping the dynamics with FELs pulses and probing its transient behaviour using the optical Faraday effect. A prompt change in its magnetization has been observed, immediately followed by coherent oscillations at a frequency compatible with the one expected in NiO for the collective magnetic excitations at room temperature [5]. Our observation is interpreted as the effect of inelastic resonant excitations stimulated by the FELs pulses, and we believe that these results may trigger future technological improvements for the FELs and future studies on magnetic materials at even faster time-scales.

[1] C. Masciovecchio et al., Journal of Synchrotron Radiation 22, 553 (2015)

[2] F. Bencivenga et al., Journal of Synchrotron Radiation 22, 553 (2015)

[3] E. Principi et al., Structural Dynamics 3, 023604 (2016)

[4] F. Bencivenga et al., Nature 520, 205 (2015)

[5] A. Simoncig et al., in preparation

10243-21, Session JS2

Single-shot linear autocorrelation of partially coherent XUV laser pulses

Andréa Le Marec, Institut des Sciences Moléculaires d’Orsay (France); Olivier A. Guilbaud, Moana Pittman, Elsa Baynard, Univ. Paris-Sud 11 (France); Julien Demailly, Olivier Neveu, Lab. de Physique des Gaz et des Plasmas (France); Sophie Kazamias, Univ. Paris-Sud 11 (France); Bruno Lucas, Fabrice Sanson, Lab. de Physique des Gaz et des Plasmas (France); David Ros, Annie Klisnick, Univ. Paris-Sud 11 (France)

Recent numerical simulations have highlighted the influence of the degree of temporal coherence in the measurement of the linear (electric field) autocorrelation of ultrashort XUV pulses generated from ASE (Amplified Spontaneous Emission) plasma-based XUV lasers or from SASE (Self-Amplified Spontaneous Emission) X-ray free electron lasers.

Linear autocorrelation measurements are usually performed using a variable-delay interferometer. The variation of the fringe visibility obtained from a multi-shot scan of the delay provides the average modulus of the degree of coherence of the radiation.

Using a partial coherence model based on a random spectral phase of the electric field of the ASE pulse, we have shown that the shape of the average modulus of the degree of coherence exhibits shoulders when the pulse duration is close to the Fourier limit duration. Our calculations are in good agreement with previously measured visibility curves for short pulse XUV lasers.

On the other hand, the modulus of the degree of coherence calculated for a single pulse (i.e. not averaged) displays a central peak related to the spectrum, surrounded by random spiky structures, related to the number of temporal modes in the pulse. Such a behaviour could be used experimentally to infer simultaneously the coherence time and the average duration of the pulse from a single-shot linear autocorrelation measurement. However such single-shot patterns cannot be observed experimentally using a multi-shot scanning delay interferometer.

In our talk, we will report on the use of a new single-shot Michelson interferometer, in which the transversal time delay introduced by the grating used as beam splitter allows to perform single-shot linear autocorrelation measurements of ASE XUV laser pulses. The presence of the spikes in the measured single-shot visibility curves and the influence of the pulse duration will be discussed.

10243-22, Session JS2

Nanofabrication of diffractive X-ray optics for synchrotrons and XFELs *(Invited Paper)*

Christian David, Paul Scherrer Institut (Switzerland)

We present recent developments in nanolithography to produce diffractive x-ray optics. For the use at synchrotrons we have developed a new generation of Fresnel zone plates produced by a line doubling approach. These lenses can resolve features down to 9 nm in the soft x-ray range and down to 15 nm in the multi keV range.

For use at x-ray free-electron laser (XFEL) sources, diffractive optics must be capable of withstanding extreme radiation loads. We show how diffractive optics made of diamond can be used for various applications including nanofocusing, beam-splitting, spectral monitoring, and ultrafast time resolved studies.

10243-23, Session 5

Soft x-ray imaging with incoherent sources *(Invited Paper)*

Przemyslaw W. Wachulak, Alfio L. Torrisi, Mesfin G. Ayele, Andrzej S. Bartnik, Joanna Czwartos, Lukasz Wegrzynski, Tomasz Fok, Military Univ. of Technology (Poland); Tomá? Parkman, Sarka Vondrova, Jana Tur?ová, Czech Technical Univ. in Prague (Czech Republic); Michal Odstrcil, Paul Scherrer Institut (Switzerland); Henryk Fiedorowicz, Military Univ. of Technology (Poland)

Recent advancements in nanoscience and nanotechnology will surely not be possible without nanometer scale resolution imaging tools and techniques such as extreme ultraviolet (EUV) and soft X-ray (SXR) microscopy. The EUV/SXR microscopy proved to be a useful tool for imaging of objects with nanometer spatial resolution, providing high optical contrast in the specific wavelength range that allows for accessing additional information about the objects. The EUV radiation is strongly absorbed in thin layers of materials, while the SXR radiation, specifically in the so called “water-window” (?=2.3-4.4nm), is particularly suitable for high resolution biological imaging, due to high achievable contrast between carbon and water – most abundant constituents of biological material.

In this talk we present recently developed, experimental, compact desk-top SXR microscope [1], the EUV microscope [2], which is at this stage a technology demonstrator and, finally, the SXR contact microscope [3]. The systems are based on laser-plasma EUV and SXR sources, employing a double stream gas puff target. The EUV and SXR full field microscopes operate at 13.8 nm and 2.88 nm wavelengths, respectively, and are capable of imaging nanostructures with a sub-50 nm spatial resolution with relatively short (seconds) exposure times. The SXR contact microscope operates at 2.88 nm wavelength radiation from He-like nitrogen ions, to produce an imprint of the internal structure of the sample in a thin layer of SXR light sensitive photoresist.

During the talk we present also applications of such desk-top EUV and SXR microscopes for studies of variety of different samples – test objects for resolution assessment and other objects such as carbon membranes, DNA plasmid samples, organic and inorganic thin layers, diatoms, algae and carcinoma cells. Details about the sources, the microscopes as well as the imaging results for various objects will be presented and discussed.

The development of such compact imaging systems may be important to the new research related to biological, material science and nanotechnology applications.

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10243-24, Session 5

X-ray absorption spectroscopy probing hydrogen in metals

Andreas Borgschulte, EMPA (Switzerland) and Univ. Zürich (Switzerland); Olga Sambalova, Yunieski Arbelo Pena, Claudio Cirelli, Davide Bleiner, EMPA (Switzerland)

X-ray absorption spectroscopy (XAS) is a widely used technique for determining the electronic structure of matter. In contrast to X-ray photoelectron spectroscopy (XPS), this technique makes use of photons only, and therefore suffers less from absorption of the probe beam, i.e., electrons or photons, respectively. This is perfectly true for hard X-rays probing, e.g., the K-edges of d-metals in metal hydrides (albeit with limited chemical information). Soft X-rays, which are perfectly suited to analyze the electronic structure of hydrogen in solids, have a limited absorption length in gases. Photons with energies of less than 50 eV (“hydrogen K-edge” ~20 eV) are absorbed in less than 1 mm at ambient pressure, which is needed for technical hydrides. Recently, we developed a membrane-based approach to study materials exposed to high hydrogen “pressures” while keeping analysis chamber under high vacuum - thus effectively achieving high pressure XPS analysis [1]. In this presentation, we demonstrate that the membrane approach originally designed for XPS can be equally well used for XAS. We show first results on the electronic structure of hydrogen in Pd as measured by in-situ XAS using a laboratory EUV source.

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10243-25, Session 5

Laser plasma soft X-ray source based on cryogenic target *(Invited Paper)*

Sho Amano, Univ. of Hyogo (Japan)

Laser plasma source based on cryogenic deposition-free target has been developed. It has a translating substrate system with a closed He gas cryostat that can continuously supply cryogenic target, and can generates continuously repetitive X-ray pulses. A cryogenic solid Ar target emitted strongly the soft X-ray in “water window” between 2.3 nm and 4.4 nm used for microscopy applications, and its power was estimated to be 140 mW with a laser energy of 1 J at a repetition rate of 1 Hz.

10243-26, Session 5

Observation of femtosecond laser spallative ablation dynamics by using soft x-ray laser probe

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The dynamical processes of the femosecond laser-induced surface modifications come to attract much attention for the micro processing. However, it is difficult to observe the femtosecond laser ablation dynamics, because of non-repetitive, irreversible and rapidly changing phenomena in a small characteristic size. Thus, the details of femtosecond laser ablation process have not been understood well. The measurement technique with the sufficient temporal and spatial resolution is necessary for the better understanding of the femtosecond laser ablation. In this study, we have developed the pump and probe interferometer and reflective imaging technique of the metal surfaces during the femtosecond laser ablation by using the laser-driven soft x-ray laser at the wavelength of 13.9 nm. The depth and lateral resolutions of the interferometer were about 2 nm and 0.7 ?m, respectively. The pumping laser used for the ablation was a Ti: Sapphire laser pulse with the duration of 80 fs pulse at a central wavelength of 795 nm, and had a gaussian spatial profile. By using the x-ray imaging technique, the time resolved image of spallative ablation dynamics of metal samples were obtained.

10243-27, Session 5

Soft x-ray laser ablation of metals and dielectrics *(Invited Paper)*

Anatoly Y. Faenov, Tatiana A. Pikuz, Osaka Univ. (Japan); Masahiko Ishino, National Institutes for Quantum and Radiological Science and Technology (Japan); Nail A. Inogamov, L.D. Landau Institute for Theoretical Physics (Russian Federation); Vasiliy V. Zhakhovskiy, Dukhov All-Russia Research Institute of Automatics (Russian Federation); Sergei Starikov, Igor Skobelev, Joint Institute for High Temperatures (Russian Federation); Noboru Hasegawa, Masaharu Nishikino, Masaki Kando, National Institutes for Quantum and Radiological Science and Technology (Japan); Ryosuke Kodama, Osaka Univ. (Japan); Tetsuya Kawachi, National Institutes for Quantum and Radiological Science and Technology (Japan)

We present a systematic experimental study of the surface modifications resulting from the interactions of both single and multiple SXRL pulses in order to confirm the development of the modified structures during multiple shots irradiation. The interactions between single or multiple picosecond soft x-ray laser (SXRL) beam with dielectric (LiF) and metals (such as gold (Au), copper (Cu), and aluminum (Al)) surfaces, were investigated. We show experimentally the possibility of the precise (~ 10 – 40 nm) nanostructuring of LiF, aluminum, copper and gold surfaces by ultra low (~ 10 - 30 mJ/cm2) fluencies of single picosecond soft X-ray laser pulse. It was also found that with single pulse irradiation, ripple-like structures were formed on the Au and Cu surfaces. These structures were different from conical structures formed on an Al surface by single shot SXRL beam irradiation. The development of modified structures, i.e., growth of hillocks on the Au and Cu surfaces, was observed after multiple SXRL pulse exposures. At the same time on the Al surface, the conical structures do not exist and ripple-like structures are observed after multiple SXRL pulse irradiation. Therefore, it was concluded that SXRL beam irradiation of various metal surfaces causes different types of surface modifications, and the changes in the surface behaviors are attributed to the differences in the elemental properties, such as the attenuation length of x-ray photons.

The atomistic model of ablation is developed for the single SXRL shot interaction with dielectrics and metals that reveals the ultra-low threshold fluency values of this process to be an effect of the high electronic pressure build-up and the comparatively low electron-ion energy relaxation rates. Our modeling show that relatively slow electron-ionic relaxation in such metals results in maintaining of the high electron pressure in the near surface region for several picoseconds, that is sufficiently long for the development of the hydrodynamic response that causes the negative pressure region formation and the nanostructuring of a thin surface layer. Additionally to study the ablation process induced by the soft x-ray laser (SXRL) pulses, we investigated the electron temperature of the irradiated material. Our measurements show that electron temperature of matter under irradiation of SXRL laser was lower than 1 eV. The model calculation also predicts that the ablation induced by the soft x-ray laser can create the significant low electron temperature. The experimental result is consistent with the theoretical considerations. Our results demonstrate that tensile stress created in dielectrics and metals by short X-ray pulse can produce spallative ablation of target even for drastically small X-ray fluencies, which open new opportunities for material nano processing.

10243-28, Session 6

Spectrally resolved lensless imaging with ultrabroadband high-harmonic generation sources *(Invited Paper)*

Stefan Witte, Matthijs Jansen, Denis Rudolf, Lars Freisem, Kjeld S. E. Eikema, Advanced Research Ctr. for Nanolithography (Netherlands)

Microscopy with extreme-ultraviolet (EUV) and soft-X-ray radiation has the potential to provide a unique window into the nanoworld. While the short wavelength radiation enables a resolution on the nanometer scale, inner-shell absorption edges of various elements provide intrinsic contrast and the ability to perform element-selective imaging. As the fabrication of efficient and aberration-free optical components becomes increasingly challenging for such short wavelengths, lensless imaging methods are a powerful alternative for the development of practical high-resolution EUV microscopes.

High-harmonic generation (HHG) sources are promising for imaging applications, as they are compact sources of fully coherent EUV radiation that fit on a laboratory scale optical table. The ability to perform interferometry with HHG sources would enable the translation of powerful optical methods such as Fourier transform spectroscopy and coherent imaging to the EUV spectral range. However, due to the short wavelengths involved, the extreme stability requirements and optical components pose a challenge. Furthermore, HHG sources are intrinsically ultra-broadband, while a major requirement in diffraction-based imaging is the need for a well characterized spectrally narrowband source.

To overcome this limitation and enable efficient imaging with HHG sources, we have developed a new imaging method based on the diffraction of coherent pulse pairs [1]. By recording a series of diffraction patterns as a function of the time delay between two coherent pulses, a Fourier-transform spectrum can be recorded at each pixel in the diffraction pattern. From this dataset, quasi-monochromatic diffraction patterns can be reconstructed throughout the full source spectrum, and the full source flux is used efficiently throughout the entire scan. Combining this two-pulse approach with phase retrieval techniques enables spectrally resolved EUV imaging, or robust image reconstruction through the use of multiple Fresnel diffraction patterns in a multi-wavelength phase retrieval scheme [2].

We have developed a common-path interferometer with sub-attosecond timing stability to produce the required tunable pulse pairs, which enables application of this two-pulse imaging method even in the soft-X-ray spectral range. By performing HHG with coherent pairs of intense pulses produced by a home-built optical parametric chirped pulse amplifier, photon energies up to 73 eV (17 nm wavelength) have been generated and used for interferometric measurements. I will present the

principles and capabilities of our approach, and show recent results on EUV imaging, spatially resolved Fourier transform spectroscopy [3], and spectrally resolved wavefront characterization of high harmonic beams.

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10243-29, Session 6

Ultrafast nanoscale imaging using high order harmonic generation *(Invited Paper)*

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Ultrafast coherent diffraction using soft and hard X-rays is actually revolutionizing imaging science thanks to new sources recently available. This powerful technique extends standard X-ray diffraction towards imaging of non-crystalline objects and leads actually to a strong impact in physics, chemistry and biology. New ultrashort pulses recently available hold the promise of watching matter evolving with unprecedented space and time resolution. Femtosecond coherent and intense radiation in the soft X-ray (? = 10-40 nm) is currently produced in our laboratory, from highly non linear frequency conversion (high harmonic generation). A high intensity UV-X coherent beam is obtained using a loose focusing geometry, which allows coupling a very high amount of Ti:Sapphire laser system energy in the HHG process. Using a long gas cell and a long focal length lens, the emitting volume can be increased by orders of magnitude compared to standard HHG set-ups. This approach, allows reaching up to 1x1011 photons per shot for the 25th harmonic (?=32nm). We have already demonstrated nanoscale imaging in a single shot mode reaching 70 nm spatial resolution and 20 femtoseconds snapshot [1]. We then implemented a recently proposed holographic technique using extended references. This technique, easy to implement, allows a direct non iterative image reconstruction. In the single shot regime, we demonstrated a spatial resolution of 110nm [2].This opens fascinating perspectives in imaging dynamical phenomena to be spread over a large scientific community. I will present recent results in the investigation of femtosecond phase spin-reversals of magnetic nano-domains [3]. Finally, I will report on recent development on noise sensitivity of the technique and perspectives in attosecond coherent imaging [4].

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10243-30, Session 6

Tunable orbital angular momentum beams in the extreme ultraviolet/soft x-ray regimes

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Optical vortices, i.e. twisted beams carrying orbital angular momentum (OAM), offer a unique capability to harness light matter-interaction processes by adding a supplementary degree of freedom. They exhibit a transversal spiral-phase structure around the beam axis, thus having a well-defined OAM, which is characterized by the topological charge, i.e. the number of 2ϖ-phase shifts along the azimuth of the light beam. These beams, typically produced in the optical and infrared regimes, are of special interest due to their additional degree of freedom over the control of light beams, making them suitable for a wide range of applications, from optical communication, micromanipulation, phase-contrast microscopy, to quantum optics, among others. There is an increasing interest to bring OAM beams into the extreme-ultraviolet (XUV) and x-ray regimes, in order to extend their applications down to the nanometric and ultrafast scales. Although x-ray optics could be used to imprint angular momentum into XUV and x-ray light, in practice such optics are challenging to fabricate and have poor throughput and limited bandwidth.

A more recent and appealing option is the direct generation of XUV/x-ray OAM high-order harmonic generation (HHG). Recently, HHG has been proven to produce XUV attosecond vortices from the nonlinear conversion of infrared vortex beams. Previous works demonstrated a linear scaling law of the vortex charge with the harmonic order. In a recent breakthrough (L. Rego et al. Phys. Rev. Lett. 117, 163202, 2016) we demonstrate that this simple law hides an unexpectedly rich scenario for the build-up of OAM due to the non-perturbative behavior of HHG. We perform advanced quantum simulations to show that, if non-pure vortex drivers are used, the OAM content of the harmonic beams is dramatically increased due to the non-perturbative intrinsic phase of the HHG process. We explore the underlying mechanisms for this phenomena and derive a general conservation rule for the non-perturbative OAM build-up, that allow us to tune the OAM content of the XUV vortex beams.

On the other hand, we explore the generation of harmonic beams with OAM content using conical refraction (CR) driving beams. CR beams are obtained in optical biaxial crystals when a beam propagates parallel to one of the two optic axes, and they present fractional OAM. We show that the XUV high-order harmonic beams are also emitted with fractional orbital angular momentum, and the properties of CR-like beams can be transferred to the XUV regime through HHG.

Our work thus presents the possibility of generating tunable OAM beams in the XUV regime –with potential to be extended to the soft x-ray regime using mid-infrared driving sources–, overcoming the state of the art limitations for the generation of OAM beams far from the visible domain. In addition, our results show that the laser-matter coupling with OAM beams is a very sensitive probe of the non-perturbative aspects of strong-field interactions, paving the route for the next generation of high-resolution XUV/soft x-ray diagnostic tools for fundamental studies and applications.

10243-31, Session JS3

X-ray production schemes from laser driven plasmas at the PALS and ELI Beamlines

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We will present data on a various X-ray production schemes from laser driven plasmas at the PALS Research Center and discuss the plan for the ELI Beamlines project. One of the approaches, how to generate ultrashort pulses of incoherent X-ray radiation, is based on interaction of femtosecond laser pulses with solid or liquid targets. So-called K-alpha source depending on used targets emits in hard X-ray region from micrometric source size. The source exhibits sufficient spatial coherence to observe phase contrast. Detailed characterization of various sources including the x-ray spectrum and the x-ray average yield along with phase contrast images of test objects will be presented. Other method, known as laser wakefield electron acceleration (LWFA), can produce up to GeV electron beams emitting radiation in collimated beam with a femtosecnond pulse duration. This approach was theoretically and experimentally examined at the PALS Center. The parameters of the PALS Ti:S laser interaction were studied by extensive particle-in-cell simulations with radiation post-processors in order to evaluate the capabilities of our system in this field. The extensions of those methods at the ELI Beamlines facility will enable to generate either higher X-ray energies or higher repetition rate. The architecture of such sources and their considered applications will be proposed.

10243-32, Session PS

Resolution of X-ray parabolic compound refractive diamond lens defined at the home laboratory

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X-ray refractive optics now is one of the most progressive areas of modern physical optics [1]. Obtaining the minimum focal spot size is traditionally regarded as one of the main X-ray focusing elements including compound refractive lenses (CRLs). CRLs have a number of important advantages over the elements, based on the principles of diffractive and reflective optics. They are compact, stable, have a simple design, easy to align, and to operate. Today, single crystalline diamond, transparent to x-rays and resilient for heat-load and radiation damage, is the best material for fabrication CRLs that are suitable for application at accelerator-based x-ray sources [2-5]. We demonstrate in this work the performance of first- generation diamond CRL by means of instruments and components that are available at laboratories. The testing results show that CRL quality is still far from perfection. Nevertheless the quality is sufficient to use these lenses in combination with powerful X-ray sources for diffraction analysis with high spatial resolution in research labs. An improvement of diamond CRLs manufacturing technology will allow reaching their ultimate performance in the nearest future. CRLs coupled with a new synchrotron-class laser-electron X-ray generator [6,7] with average flux of 1012–1013 phot/sec pave the way for the development of the focusing system with spot size ~1 micron in the energy range of > 30 keV.

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10243-33, Session PS

Evaluation of laser-electron X-ray source and related optics for X-rayimaging and X-ray diffraction analysis

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Laser-electron X-ray sources (LEXS) are expected to fill a few orders of magnitude gap between large X-ray facilities and conventional sources existing in brightness, intensity, tunability, sizes and cost [1]. They promise to bring capabilities and flexibility of a synchrotron to research and industrial labs, regional universities and clinics and therefore change the present landscape of X-rays applications [2,3]. LEXSes combine recent developments in accelerator and laser technologies and reveal wide possibilities to compromise various X-ray sources and beam demands made by material science applications considered in this work. The source parameters can be derived from the beam requirements at the surface of a sample and available X-ray optics. Then the source yields the parameters of main LEXS components: accelerator and laser units, optical storage device and the scale of a system in general [4,5]. This approach is applied to design a LEXS system for academic lab which now uses standard analytical equipment. The considered applications include phase, dark field and attenuation contrast X-ray tomography of a small animal [6], atomic pair distribution function analysis of nanocrystals, liquids, amorphous and molecule biology materials [7-9] using high energy X-ray. In combination with X-ray refractive optics a LEXS is well suitable for structural studies of materials at extreme pressure created in diamond anvil cells [10].

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10243-34, Session PS

XUV-frequency control and the cut-off law for high harmonics generated using the optical gating

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High-harmonic generation (HHG) produced by interaction of IR-radiation in gaseous targets is one of the intensively studied sources of XUV radiation during recent decades. For some applications, there are several aspects needed to be improved. In our work, we focus on controlling the XUV properties using special configurations of the IR-field. In a basic configuration, XUV-field is generated by a linearly-polarised laser in a pulse regime. It leads, in frequency domain, to odd multiples of the IR-field frequency. A way to control the XUV is to employ a more advanced configuration of the IR-field. We have chosen so-called optical gating

for our study. The optical gating is using an elliptically polarised IR-pulse superposed with its temporally delayed counter-rotating replica. The XUV is effectively generated only when the resulting field is nearly linear. This configuration has been investigated theoretically in details.

First, we show an extent of the cut-off as compared to the linear case. We have performed simulations for investigating the modified cut-off as a function of the gate-intensity, ellipticity of the pulses and the pulse-delay.

Next, the peak intensity of the replica has been allowed to change with respect to the peak intensity of the original pulse. We have simulated cases with two delayed counter-rotating elliptical pulses of different amplitudes and demonstrated, for the first time, that it allows for controlling XUV-photon frequency. These results are of prime interest in particular in the context of tomography where controlling the cut-o? of harmonics spectra allows for defining a good spatial resolution of the molecular orbitals. Being able to tune the central frequency of the XUV comb will allow for studying the orbitals of large molecules.

For our purposes, only the microscopic aspect of the XUV generation has been considered. All results have been retrieved from simulations based on the Strong Field Approximation (SFA) for a Hydrogen atom.

10243-35, Session PS

Radiation properties of Ni-like molybdenum X-ray laser at PALS

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We present successful Ni-like molybdenum x-ray laser (18.9 nm) demonstration with grazing incidence pumping and its comprehensive diagnostics. This source of EUV radiation was first experimental realization of transient x-ray laser at the PALS laboratory. The experiment was performed on Ti:Sapphire laser system with central wavelength 810 nm and repetition rate of 10 Hz. Pumping scheme has been realized by time-profiled beam which included long prepulse followed by short main pump pulse. Experiment was demonstrated with very low pumping demands respect to energy that was less than 500 mJ. The gain medium in shape of plasma column with length 3.5 mm and 4.3 mm was created by focusing of collimated laser beam incident on spherical mirror with radius r = 1 m. Complete analytical calculation focused on linear focus formation was performed. This calculation included focus length, intensity distribution along the line focus and exploring travelling wave creation.

The EUV spectrum have been observed with spectrometer which was composed of gold reflection grating with variable period in grazing incidence geometry and back illuminated x-ray CCD camera. According to values of gain-length product which were around 13 we can estimate x-ray laser working near regime of saturation. The total output energy in single EUV pulse was precisely established like 100 nJ. We have also investigated complex structure of far-field pattern which is typical for transient x-ray lasers. Experimental data from far-field image was treated by theory of first order speckle statistic, i.e. intensity statistics at a single point in space and time. This theory states that the origin of intensity fluctuation in far-field can be explained like interference pattern of elementary coherent components of radiation with random phase change. The random phase changes result from propagation radiation through amplifying plasma gain medium with inhomogeneities of refractive index in shorter lengths than length determined by coherence time.

Intensity statistics can give information about number of independent speckle patterns. We have tried to investigate dependencies of number of modes with respect to different pumping conditions. We found out a modal dependence which can be explained due to lineshape narrowing of a propagating EUV pulse in gain medium. The dependence has been supported by a simple 1D radiative transfer simulation which provided information about evolution of the spectral line shape profile during EUV beam propagation. Applying proposed method for characterization of the far-field pattern we could estimate pulse duration which quite well correspond to the expected value. Experimental data from far-field can be also analyzed by applying generalized Van Cittert-Zernike theorem which in general relates field correlation function at source with intensity at far-field. If we assume real situation of partially coherent radiation then we can estimate upper bound dimension of the EUV source.

The high-energy pulses which are typical for this kind of sources make them suitable for many photon-hungry applications, but on the other hand the inhomogeneous intensity profile and coherence properties still need to be subjects of further investigations.

10243-37, Session PS

An approach to reflection X-ray microscopy below critical angles

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There is a quest for new knowledge and methods to study various materials and processes on surfaces and interfaces at the nanoscale. This is about ablation, phase transitions, physical and chemical transformations, dissolution, self-organization etc. To observe it, is necessary to have a wavelength providing an appropriate resolution. Higher resolution can be obtained with shorter wavelength. On the other hand, in surface modification, ablation, study of buried interfaces etc. an important role plays the penetration length of radiation into material which crucially depends on the wavelength and angle of incidence. Finally, X-ray sources and optics are more expensive and less available for shorter wavelengths. Considering these factors in various problems of nano-physics and nano-technology the observations are carried out using radiation with a photon energy of 0.1-10 keV. As far as surfaces and films are investigated it is reasonable to use a microscope in the reflection mode. However, in this spectral range substantial portion of radiation is reflected only at small grazing angles (e.g. ≤ 10°). Thus, the idea of grazing incidence reflection-type X-ray microscope appears. In this paper, we consider one of the possible schemes of such optical microscope. The analysis is based on the extension of the Fresnel propagation theory to tilted objects.

10243-38, Session PS

Ultrafast x-ray fluorescence of L? line of selenium atoms for drug candidates screening

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We developed ultrashort x-ray radiation sources with high-repetition rate ultrashort laser and applied to the elemental analysis and the screening of drug candidates. The Ti:Sapphire laser pulse has a wavelength of 800-nm, pulse energy of 12mJ, repetition rate of 1 kHz, and pulse duration of 36 fs. Also a vacuum target chamber, an X-ray spectrometer chamber, energy dispersive X-ray spectrometer system with HOPG and X-ray CCD was constructed. In order to overcome the weak brilliance of laser-driven x-ray, we monitor the x-ray fluorescence which is the unique fingerprint of elements and most sensitive x-ray probe. Also, in order to enhance the S/N ratio, we use the detector gating method which will enhance the S/N ratio up to million times. At the X-ray fluorescence pump-probe experiment, by irradiating the ultrashort K? x-ray generated from the aluminum tape target to the selenomethionine substituted proteins which is known to be the inhibitor of the glutamate vesicular transporter, X-ray fluorescence of L? line of Selenium atoms in the proteins is monitored. In this presentation, detailed experimental method and the results will be reported.

10243-39, Session PS

Development of high-flux high-order harmonic generation at PALS and ELI-Beamlines

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High-Order Harmonics Generation (HHG) process is produced by interaction of a linearly polarized intense laser pulse with atoms, during which odd harmonics of the incident laser pulse are generated. While being compact and inexpensive, those table-top sources are wavelength-tunable in the XUV range and display excellent both spatial and temporal coherence properties, allowing implementing various imaging techniques such as Coherent Diffractive Imaging (CDI) and ptychography.

One of important features of HHG source is that the generated XUV pulse duration is ultrashort and can be reduced down to a few hundreds of attoseconds, thus making possible to investigate the ultrafast dynamics of atoms or molecules. Moreover, the high-harmonic polarization can be tuned from linear to circular through elliptic, which gives opportunity to carry out polarization-sensitive measurements in matter or molecular physics.

Despite those attractive characteristics, the number of photons remains limited and it is given by low conversion efficiency inherent to HHG process, therefore restricting the range of possible applications.

Therefore finding ways for increasing HHG energy output arises great interest nowadays. In order to overcome listed above limitations and enchance harmonic beam energy yield, two techniques were studied during experimetal campaings at PALS Center (Prague).

First, we use an approach for improving harmonic output by optimization of experimental parameters and achieving phase-matching conditions. Next, we implement loose focusing geometry with high energy of driving pulses in order to increase the yield of the harmonic signal, allowing the source to become convenient for applications that require pulses with high photon numbers.

In this work we present a study of the scaling of output properties of the beam generated through HHG on the f-number of the laser focusing. Experimental parameters for focal lengths 0.5 m, 2 m, and 5m in optimum conditions for phase-matching (driving intensity, gas cell length and pressure inside the cell) were investigated allowing extraction of the scaling of the output parameters, such as XUV energy, conversion efficiency and divergence of the harmonic beam. The high harmonic beam with energy 40 nJ per pulse was generated in Ar with focal length of 5 m.

Further implementation of longer focal lengths is expected to be realized at ELI-Beamlines facility, providing high output flux of high harmonic source. The expected wide wavelength range of HHG source at ELI-Beamlines will make it suitable for broad range of applications, among them are pump-probe, CDI and ellipsometry experiments.

10243-40, Session PS

Laser-driven liquid-metal-jet plasma system PXS for pump-probe spectroscopy and diffractive imaging

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A fs-pulsed laser-induced liquid-metal-jet plasma target (Bi, In, Pb) generating hard X-ray radiation in the energy range between 3 keV and 24 keV will be installed and commissioned at ELI beamlines, experimental hall E1, utilizing ELI's high repetition-rate / high pulse-energy laser system L1. The deployment of a laser power up to 5 TW enables a photon output > 109 photons per pulse and line in 4? sr. Two X-ray tubes and an additional online characterization tube allow the conduction of experiments both in transmission and reflection geometry at the same time. The compact table-top PXS will provide a wide range of experimental setups for scientists and beamline operators. Methods and procedures can be studied using the PXS as a high brilliance, short-pulsed laboratory source, e.g. biomedical (coherent diffractive) imaging and time-resolved, ultrashort-pulsed X-ray spectroscopy. In collaboration with XFEL GmbH, ELI Beamlines' PXS will carry out experiments on weak 3D diffraction data[1] using optimized algorithms for table-top secondary sources.

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10243-41, Session PS

XUV generation under the action of pico- and nanosecond laser pulses on nanostructured targets

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Laser-produced plasmas are intense source of XUV radiation that can be suitable for different applications such as extreme ultraviolet lithography, beyond extreme ultraviolet lithography and water window imaging. We have investigated the spectral behavior of the laser produced plasmas of close-packed polystyrene microspheres and porous alumina targets covered by a thin tin layer in the spectral region from 2.5 to 16 nm. Ekspla SL312P 150 ps and Surelite 7 ns Nd:YAG laser pulses were focused on nanostructured targets coated with tin (Sn) placed in a stainless steel vacuum chamber pumped to a pressure of 1.6?10-6 mbar. Spectra were recorded using a 0.25-m flat field grazing-incidence spectrograph, equipped with a variable groove spaced grating with an average value of 1200 grooves/mm and a thermoelectrically cooled CCD camera with 2048 pixels in the spectral direction. The intensity dependence of the recorded spectra was studied; the conversion efficiency (CE) of laser energy into the emission in the 13.5 nm spectral region was estimated. We have observed an increase in CE using high intensity 170 ps Nd:YAG laser pulses as compared with a 7 ns pulses.

WS100-18, Session PS

An all-reflective polarisation rotator

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The possibility of continuous adjustment of energy, or polarization state of high peak intensity ultra-short laser pulses is desirable in several applications. In most cases changing the energy continuously is difficult without affecting the time and spatial properties of the pulse. This can be done by rotating the polarization plane of the linear polarized laser beam and transmitting it through a polarizer. In some cases laser-matter interactions require the online rotation of the polarization plane, or changing linear polarization to elliptical. In most cases wave plates are used to do this. However wave plates have several disadvantages. Short laser pulses and hence broad bandwidth require using achromatic retarding plates. Those have a limited scalability in size and because of the substantial thickness can lead to the pulse broadening and inaccurate polarization rotation. A polarization rotator based on mirrors is a preferable alternative to wave plates especially when used in high average power or high peak intensity ultra-short laser systems. It has the advantage that the spectral transfer function is widely selectable, moreover the device is scalable for large beam diameters and the damage threshold is limited by the mirrors only, which is considerably higher than for wave plates. Contrary to wave plates, a reflective polarization rotator creates no post-pulses. Thus, the probability to generate related pre-pulses after recompression is minimized. The polarization rotator proposed consists of three mirrors fixed on a common plate which can be rotated around the optical axis. This rotates continuously the polarization plane of a linearly polarized laser beam at any desired angle. The device is a mirror - type analogue of the Dove prism, which is able to rotate an image continuously. If a mirror is polarization inactive the rotation of linear polarization produced by a mirror is exactly the same as the rotation of an image seen in the same mirror. This device is useful when the incoming linearly polarized beam has a stable polarization angle and there is a need for fast switching of polarization to either horizontal or vertical directions. Rotating the mirror assembly through 180° the plane of polarization can be continuously rotated through 360°, furthermore the input and output beams are collinear, therefore it is easy to insert the device into any existing setup. We present the conceptual design of the device and results of proof of principle experiments. Aluminum, silver, gold and dielectric mirrors were tested in the setup. Our measurement and calculation results show that upon reflection on a mirror, reflectivity ratio and phase shift difference for the s and p polarization components have influence on the polarization purity of the beam. Therefore the performance of the polarization rotator depends on the type of the mirror used, furthermore the polarization purity can be tuned with changing the angle of incidence on the mirrors.

WS100-19, Session PS

Pulse compression optimization of a picosecond high average power thin-disk laser

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We have developed picosecond high average power laser system based on an Yb:YAG thin disk. The system utilizes chirped pulse amplification. The chirped volume Bragg gratings (CVBG) are used for pulse stretching and compression. Additional chirped fiber Bragg grating (CFBG) is used in the pulse stretcher for optimization of the pulse width of the output pulse. The stretched pulses of an Yb-fiber laser oscillator at 1030 nm wavelength are injected into the first regenerative amplifier with linear cavity operating up to 100 W of the average output power. The second regenerative amplifier with ring cavity boosts the output power above 200 W.

The amplified pulses, from either of the stages, are compressed by the CVBG from 500 ps pulsewidth to few picoseconds pulsewidth. Use of CVBG enables to make the system compact and robust. The footprint of the CVBG is only few square centimeters. The Treacy type compressor with two diffraction gratings would require footprint of few square meters and is more demanding for alignment.

However, the CVBGs can suffer from thermal load caused by the residual absorption of the beam to be compressed at average power at the 100 W level and more. The axial and transversal temperature gradients in the CVBG are results of reflection of different spectral parts in different depths of the grating and Gaussian like beam shape, respectively. The inhomogeneous temperature inside the CVBG distorts the original periodicity of the grating, which leads to the mismatched pulse compression and worsening of the beam quality. The effects of the CVBG thermal load at different power levels on the pulse compression, spatial chirp, and M2 of the beam will be presented for different power levels. Further, results on the improvements of the compression by various approaches will be shown.

WS100-20, Session PS

Light hydraulic effect in laser nanodiamond synthesis, optimizing parameters for the output increase

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Nanodiamonds first discovered in 1963 in detonation soot are highly efficient in various processes, in electroplating, polymer compositions, polishing, lubricants and sintering [1]. However, the implementation of nanodiamonds in the industry is still restricted due to their insufficient homogeneity mainly caused by the non-controlled process of their fabrication by the detonation of explosives in closed chambers. Light Hydraulic Effect (LHE) was applied for laser assisted synthesis of pure and uniform nanodiamonds [2]. This method is based on the focusing laser radiation of high power density in liquid at some distance from specially prepared hydrocarbon target. A few approaches of technology optimization were considered theoretically: using solid state Q-switch lasers and fiber lasers with laser pulses in the range from femto to nanosecond pulse lengths with the delivered power density varying in the range of 10^7 – 10^10 W/cm^2 and maximally suitable repetition rate. Our lab technology proved that the optimization of laser parameters has a clear promise of raising the nanodiamond output by 2-3 orders of magnitude.

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WS100-21, Session PS

An approach to stabilization of a laser beam by using a modified Stewart platform

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Today, lasers are a major part of the various technological devices used in various machine tools to cut, weld or cure polymers. During the manufacturing processes, various vibrations may occur, which can have an influence on the shape or quality of produced parts. Such vibrations can be caused by the equipment design, the units' location, and various external vibration sources. Despite their minor values, these vibrations can cause manufacturing errors when the lengths of objects to be produced are measured in tens of microns. To prevent possible errors, laser beam stabilization should be used.

We present a new mechanism for optical stabilization of a laser beam used a modified Stewart platform. The presented compensation system consists of four linear drives decreases the number of freedom degrees of the Stewart platform to three: two tilts around OY and OX axes and linear movement along the OZ axis. This design sustains the center of the moving platform on the optical axis of the system.

Use of such architecture with three degrees of freedom allows it to compensate its occasional deviations from the fixed optical axis by tilting the lens around two axes. A focal setting can be tuned by moving the platform along the optical axis.

Linear drives, stepper motors with ball screws or piezo motors can be used to vary sliding shafts lengths. A lens or prism can be mounted on the moving platform as the compensating element.

To make corrections in real-time mode, a closed loop should be organized. Therefore a gyroscope and three or more accelerometers should be placed to track vibrations. In addition, the external high-speed camera is used. The camera is necessary to control the laser beam position. Data from sensors and camera will be processed using a Kalman filter. According to processed data, the parameters of proportional–integral–derivative controller will be adjusted. A result of its rigidity compensated positioning error and definite positioning.

This system was modeled. Specific parameters were calculated for given angular ranges and positioning coordinates. Also, specifications for sliding shafts were stated. To solve the problem of automatic vibration compensation and adjustment of a position of the laser beam during movement, optimal trajectories of the platform orientation changes were chosen.

It can be noted that sliding shafts acceptable region are non-convex, hence, the platform moves from one position to another along a curve, but for angles fractions, it can be assumed as moving along a straight line. Because the picture represents data for a large-size mock-up, the convex part is of noticeable size. For the actual device, it will not be so large. The platform mock-up was constructed to match optimal moving joints parameters and couplings with positioning elements.

WS100-22, Session PS

A design of an optical fiber delivery system for technological equipment

Yuri V. Fedosov, Maxim Y. Afanasev, Galina E. Romanova, ITMO Univ. (Russian Federation)

In recent years, widespread use of industrial laser systems has attracted attention to problems of development of an optical fiber delivery system for laser sources of a few watts power. Such systems can be exemplified by different kinds of technological equipment, for instance, sheet cutting machines, engraving machines, welding machines, machines for treatment photopolymers, etc.

Laser sources applications are characterized by their start-stop operation mode, moreover, turning the beam on and taking it off should be performed immediately – and the operating result depends on it in many cases. Such devices are based on the schemes with a large number of movable optical elements such as lenses and mirrors . The beam is controlled by turning the laser on and off. The main disadvantages of the mentioned schemes are the optical elements redundancy leading to power losses and design complications. The other typical feature is a simplified deflecting system, utilizing a flat mirror, deflecting the beam into the same area of the beam dump. This leads to beam dump deterioration because of irregular wear of the absorbing surface. In this work the general design specifications of an optical unit with a simplified optical scheme, allowing increased dexterity in laser beam control with the simplifying optical scheme is considered.

The proposed optical system consists of a solid-state UV laser placed on the same visual axis with a filter and convergent lens and an optical fiber. The filter is a transparent plate, made of blue-green glass intended to absorb emission of 580–700 nm wavelength.

A convergent lens is intended to focus the laser beam on the face of the optical fiber. The laser beam deflecting system is placed between the laser beam source and the filter. Its general purpose is to immediately turn the laser emission on and off, which is not possible by switching the laser power on and off. The deflecting system is comprised of two mirrors: flat mirror of a polygonal section and a spherical scattering mirror. The flat mirror can move perpendicular to a laser beam. Returning the flat mirror to its initial position is supplied by the spring. When the flat mirror is located in the upper position, the beam first deflects from it and then deflects from the spherical scattering mirror, then it falls into the beam dump. Beam presence is controlled by the photosensor.

The scattering mirror is used for laser beam attenuation and for continuous beam dump exposure. As a result, the beam dump heats regularly and absorbs beam energy more effectively. The case of the optical unit is made of aluminum alloy and it forms an additional cooling supply for the laser beam source and solenoid. Fan cooling is also provided. The laser beam dump is an open conical cavity, in which the conical element with its spire turned to the emission source is placed. Special microgeometry of the internal surface of the beam dump is suggested for better absorption effect.

WS100-23, Session PS

An application of genetic algorithm methods for optimization the moving trajectory during laser processing

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Intelligent technological equipment is intensively developing at present. Their basis is formed by a mechanism moving a terminating device along the specified trajectory. Obviously, its efficiency depends on the moving trajectory and speed of the mechanism. Let us consider the device for selective polymer curing. The device is comprised of a mount, on which an object is fixed, a laser head moving in two directions installed above the mount, and a laser beam source optically coupled with the laser head.

The following is proposed. At first, the grid applies on the area to be processed. The processing trajectory is represented as nodes and plenty of verses and is split into the segments, which are enumerated in the list. Each segment in the list represents the trajectory direction, and their order defines the tracking sequence. The trajectory tracking time is formed by the time taken to track all the segments and the time to perform all the auxiliary passes at the maximum speed.

The time of the auxiliary pass between processing parts can be represented as a function of four arguments: two coordinates of the point to switch the laser off (passive mode), and two coordinates of the point to switch the laser on (active mode). Accounting that X and Y drives of a machine can work independently, a free run time between two active modes will be proportional to the maximum increment for each axis and free run total time will be the sum of the transit time of each segment of the path. Each segment of the trajectory is defined by coordinates of its start, end and tracking direction and is processed during the active mode. The segments list completely defines the processing trajectory. According to that, the trajectory optimization problem can be stated as defining the segments tracking sequence and their orientation (start and end), reduces the processing time, to a minimum.

This problem can be solved using genetic algorithms. The coding and crossover operator are similar to the crossover used to solve the traveling salesman problem. So the number of auxiliary paths can be reduced along with the genetic algorithm, with added segment tracking direction.

Each individual gene contains information about a segment number and the direction of processing for determining the movement of the laser head along the segment. The sequence of genes in the chromosome determines the sequence of laser processing of individual segments, and thus, the chromosome uniquely encodes the trajectory of the laser head in the machining process of the product.

Given the feature task, one must use the crossing-over, keeping all the genes included in the parent chromosomes. If it will not execute this condition, a portion of the segments to be processed will not be processed and some segments are processed twice. This type of crossing-over was studied and applied to solving problems of the traveling salesman by genetic algorithms.

WS100-24, Session PS

Design of the compact temporal coherent beam combining module for high power femtosecond pulse laser

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Recent, the demands of applying a femtosecond pulse laser have increased in precise laser manufacturing fields. A femtosecond pulse laser used in laser manufacturing requires the high peak and average power so that the femtosecond pulses should be amplified significantly. In typical, the chirped pulse amplification (CPA) to stretch the pulse temporally and amplify the pulse is widely used in this field because it can avoid the damage of the amplifying medium. When the pulse energy is higher than the damage threshold of the medium, however, the CPA technique still has practical limitation. In order to overcome this limitation, several techniques have been proposed and one of them is divided pulse amplification (DPA) as a good candidate for obtaining the ultra-high-energy pulse.

In this investigation, we propose a compact divided pulse amplification (DPA) system based on the multi-pass interferometric technique for industrial application. The proposed module is focused on the temporal DPA technique and combination of temporal and spatial DPA module can generate the high amplified pulse.

The seed pulse from a femtosecond pulse laser is incident to the module and the polarization can be adjusted by a half-wave plate, which enable one pulse to go through a polarizing beam splitter (PBS) and the other to reflect by the PBS. The transmitted pulse (p-pulse) had no time delay while the reflected pulse (s-pulse) experiences multi-pass in the configuration. The size of the module is 0.3 m x 0.3 m and the divided two pulses has the long time delay approximately 6 ns, which corresponds to the optical path difference of 1.8 m because of the multi-pass configuration. In addition, the designed temporal DPA module can be used in both of pulse dividing and pulse combining. When the divided pulses are incoming in the opposite direction of the module, the delayed pulse can go through the module without the delay and the other experiences the optical delay. Finally, two pulses can be combined with each other in the aids of a precise motion stage for the coherent pulse combing.

The total optical path reaches up to 1.8 m but the size of the system is approximately (0.3 m x 0.3 m) because of the multi-path configuration. For combining the divided pulses, LOSCET method based on the modulation and demodulation technique is used and the pulses can be coherently combined to generate constructive interference. As the feasible experimental results, the femtosecond pulses were successfully divided and combined and it is expected that the proposed system can be applied to achieve the industrial high power femtosecond pulse laser.

WS100-25, Session PS

On the multiscale 3D modeling of laser melting of metal powders

Alexander V. Dubrov, Fikret K. Mirzade, Institute on Laser and Information Technologies (Russian Federation); Vladimir D Dubrov, ILIT RAS - Branch of the FSRC "Crystallography and Photonics" RAS (Russian Federation)

This work is aimed at creating computational software tools to conduct predictive 3D modeling of microstructural properties of the material produced using the technology of high-intensity laser melting of metal powders. The consumer properties of the products are predetermined among others by the features of the material microstructure. An important fact is that in a number of cases there is no direct inheritance of the original microstructure of the powder material. The resulting microstructure is created dynamically with regard to instantaneous environmental conditions, and the formation of crystalline microstructures and their morphology evolution significantly depend on the macroscopic processes of heat and mass transfer and hydrodynamics of the melt. Such macroconditions are defined by the technology process parameters as well as by the characteristics of the manufactured product and its manufacturing strategy. Thus, for the physical and mathematical description of the problem the physical processes can be naturally presented in the form of a structure of the process groups that take place at several scales and show mutual influence.

We propose a two-level model of melting of metal powders with high-intensity scanning laser radiation. The feature of the approach is that different physical models are used to describe the processes at different spatial scales (macro- and mesolevels). The model of macroprocesses is based on the system of nonlinear differential equations of heat conduction, fluid dynamics, diffusion of components, as well as evolution of the free surface. At the mesolevel the evolution of the microstructure of solidification is considered using the phase field model equation. It operates with the field parameter that characterizes deviation of the system from equilibrium. The solidification process is regarded as a change in this field, called the order parameter. The phase field equation takes into account the influence on the processes of growth and morphology of the crystal (dendritic) structures of such important factors as the diffusion of heat, release of crystallization heat, anisotropy and the melt supercooling.

The numerical simulation is performed applying the method of finite volumes. In the development of the software the open source library of C++ classes for mathematical calculations and numerical simulation OpenFoam is employed. It focuses on the work in the high-performance software and hardware cluster environment with application of parallelization techniques. The numerical implementation of the macroscale model is held in the paradigm of VOF method. The model allows for the effects of surface capillary forces, thermocapillary convection, molecular and convective heat transfer. The test calculations have been carried out to verify a number of process characteristics. We have obtained the calculated 3D macrofield distributions of the physical quantities (temperature, fluid velocity fields) for different parameters of the technical process. The data obtained are compared to the results known from the literature. Thus, the numerical implementation and verification of the macroscale model have been performed. The transition to integration with the mesoscale model have been prepared. The link of the technical process parameters with the conditions of the material microstructure formation have been set through the macrolevel. This circumstance is necessary for monitoring and control of the properties of the synthesized material.

WS100-26, Session PS

A phase field study of stress effects on microstructure formation during laser sintering of powders

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Laser powder sintering is a well-established manufacturing process for rapid prototyping of fully dense metal components. It involves the supply of powders into a laser-heated spot where the powder is melted and forms a melt pool, which quickly solidifies. During the laser sintering (LS), several complex phenomena occur as the laser beam interacts with both incoming powders and the substrate. These phenomena include thermal transport, fluid flow, mass transport, and solidification, as well as others. Many researchers [1] have studied the macroscopic temperature, concentration and fluid velocity fields during the LS. However, the modeling of microstructure evolution of the solidification (mesoscale process) has received a little attention. Mechanical properties of fabricated materials strongly depend on their microstructure. The prediction and control of microstructure play crucial roles in high-intensity laser additive manufacturing. The existence of mechanical stresses, which are generated during the LS, is also of great importance. Most of the defects (macrosegragation, pores), formed in materials are a result of stresses in the solid-liquid mushy zone. Therefore, useful methods for modelling stresses during microstructure formation have been required.

The phase field modeling [2] is one of the most powerful approach to modeling and predicting mesoscale morphological and microstructure evolution in materials. The author previously used a simplified phase field model in which only elastic behavior was included to show stress/strain evolution during binary alloy solidification [3].

In this contribution, the elastic-plasticity constitutive relationship is considered to study the effect of stresses on microstructure formation during LS of metal and alloy powders. Fundamental equations accounting for the coupling effects among phase variable, an orientation variable, thermal and stress/strain fields have been derived based on the principle of entropy production positiveness, in which thermal expansion, anisotropy effects, transformation dilatation, and stress dependency on phase transformation are considered. From the analysis of the system of simplified equations, the physical meaning of the parameters in the evolutionary equations is identified. The possibility to describe the process of structure formation at the interface during the melt crystallization is discussed. The analysis of the linearized stability problem makes it possible to find a spectrum of wave numbers of unstable perturbations. It is shown, that, in addition to the thermal and mass transfer processes, the elastic field generated by the stresses is another important factor that controls the instability mode. An increase in stress values increases the maximally wavelength of the unstable perturbations. Disturbances growing with the greatest speed determine the characteristic size of the structure at the solidification front.

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WS100-1, Session 1

Laser-driven beams for nondestructive imaging and inspection in medicine, security and nuclear waste management

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Accelerators driven by the interaction of an ultra-intense laser with matter have been in development for over a decade. The extraordinarily high accelerating gradients achievable are several orders of magnitude higher than any conventional accelerating system and the x-ray emission can be tuned in energy simply by switching the targets that the laser shoots. This makes a laser-accelerator a versatile source, capable of imaging a wide range of samples for many high value sectors – from medical samples through to imaging large dense objects such as nuclear waste barrels. For imaging and inspection the laser-driven concept also has several major competitive advantages, namely that it can generate x-rays from a micro-scale point source for high resolution projection radiography and can operate in multi-modal delivery generating, in parallel, beams of electrons, neutrons and even muons for complimentary inspection techniques.

Presented here is an overview of demonstration experiments carried out over the last 24 months at the STFC Central Laser Facility, using the petawatt-class lasers Gemini and Vulcan, in collaboration with Imperial College London, NHS England, Defence Science and Technology Laboratory, University of Strathclyde, Queen's University Belfast, University of Bristol and Sellafield Ltd. Micro-CT of biological samples, laser-driven x-ray radar for depth profiling and radiography of dense objects are profiled as examples of recent activity.

The CLF is now developing high repetition rate capability, via its novel DiPOLE system – a high average power, diode-pumped laser system capable of delivering 100 J pulses at 10 Hz. This step-change in high-energy laser technology is vital for realising laser accelerators for important and high impact applications and for transferring the technology from laboratory to commercial exploitation.

WS100-2, Session 1

DUV high power lasers processing

Masakazu Kobayashi, Kouji Kakizaki, Hiroaki Oizumi, Toshio Mimura, Junichi Fujimoto, Hakaru Mizoguchi, Gigaphoton Inc. (Japan)

A laser processing is widely applied to cutting, drilling, welding, bending and surface treatment in industry. Lasers with a wavelength of 1 ?m are mainly used and the processing is realized by melting materials. This thermal process has a high productivity but the processed surface is hard to use for precision machining.

In order to get finer processing surface, many researches on short-pulse lasers (femtosecond(fs) lasers) have been conducted. However most of them are the application to micro-machining because fs laser power is low for macro-machining. Another approach is to use short wavelength lasers in DUV (193, 248nm). DUV processing could reduce the thermal influence and damages in a material by direct photon absorption because photon energy of a DUV laser is much higher than that of the infrared. More than several thousands of DUV lasers are installed and operated in semiconductor manufacturing for leading-edge lithography process and in FPD manufacturing for poly-Si crystallization. We have developed high power DUV lasers. One is a 193nm excimer laser with the output power of 120W and the second is a 248nm one of 400W.

This report is focusing on two materials which are classified in wide band gap.

A glass is a popular and economical material for industry. Advanced FPDs in smartphone productions recently require fine machining results in cutting and drilling. The conventional infrared laser processing is not appropriate to precise glass manufacturing because the edge surface of glass is heated and melted to get the distorted figures. Another material is CFRP, the use of which in aerospace and automotive industry is rapidly growing due to the light weight and superior performances. The conventional machining, however, has several problems to generate serious mechanical damage and inadequate surface roughness of cut walls. The laser processing with no thermal damage, low roughness and easy automation is highly expected as an alternative method.

This report will demonstrate the latest processing results with DUV lasers.

Wavelength and material property dependences on DUV processing will be discussed.

WS100-3, Session 1

Characterising laser-plasma driven X-ray sources for industrial radiography applications

Chris Armstrong, Univ. of Strathclyde (United Kingdom); Ceri M. Brenner, David Neely, STFC Rutherford Appleton Lab. (United Kingdom); Paul McKenna, Dean Rusby, Univ. of Strathclyde (United Kingdom)

During intense laser-plasma interactions with solid targets, fast electrons are accelerated through the target and produce a bright x-ray pulse, through bremsstrahlung and line emission. These sources are capable of imaging complex industrial samples due to its small source size (<100um), high flux, and energetic spectrum (>1MeV). These three factors combined with the short pulse duration (ps) intrinsic to laser-plasma interaction give laser driven systems an edge over conventional x-ray sources. The source size dictates the resolvable features from the sample, the flux dictates the contrast of the image, and the energetic spectrum allows large, dense, objects to be imaged. Characterising these sources to understand the limits available in both a scientific and application driven sense is paramount to bringing this technology forward into widespread use among non-destructive testing communities.

Presented here are methods to exert control over the source size and the emitted spectrum. We discuss a combination of results from experiments on the Vulcan laser system at the STFC Central Laser Facility, and simulation work using the Monte-Carlo code GEANT4 completed by the authors. The results are discussed in line with imaging large scale industrial objects, exploring the trade-offs between changes in the emission to optimise the imaging capability. With that in mind we discuss results from conventional x-ray converters, such as thick tantalum, and thin foil targets typically excluded due to low yield.

WS100-4, Session 1

Industrial applications at HiLASE

Michael Pisarik, HiLASE (Czech Republic)

A review of the capabilities of HiLASE centre lasers in selected applications, including precise drilling and cutting, surface modifications, material modifications, LIDT measurement and scientific applications in scaling of average power up to 1kW level at the fundamental wavelength (1030 nm).

We have three fully operational high pulse energy laser systems covering three regimes, including the high-pulse energy, low repetition rate PERLA A system (100 mJ, 1 kHz, 2 ps), high-average power, high repetition rate PERLA C system (0.1 – 5 mJ, 100 kHz, 2 ps) and the high energy BIVOJ (DiPOLE) system (100 J, 10 Hz, 10 ns). Along with these lasers, there are processing stations for 1 ?, 2 ?, 4 ? and 5 ? (specialized for picosecond lasers) in the laser laboratories at HiLASE centre.

Applications are divided by laser systems, pulse duration, processing stations and industrial cooperation in the dedicated experimental halls. There are fully operational nanosecond and picosecond laser distribution systems from laser laboratories to experimental halls in application areas. Application areas consist of 3 experimental halls and a dedicated chamber for laser induced damage threshold (LIDT) testing. The LIDT chamber fully complies with ISO 21254 and measurements are provided 1-on-1, n-on-1 and r-on-1 in nanosecond or picosecond regime.

The first experimental hall will come into service in February 2017 and is dedicated to applications requiring energy up to 10 J, like laser shock peening and material modifications. With our UK teaming partner, we would like to investigate other applications requiring energies up to 100 J per pulse. Other experimental halls are designed for ultrashort pulse laser biomedical, interaction studies or multicolor interaction applications and will come into service throughout 2017.

WS100-5, Session 2

Space debris removal

David Neely, STFC Rutherford Appleton Lab. (United Kingdom)

No Abstract Available

WS100-6, Session 2

Periodic surface structures induced by single frequency-converted picosecond laser pulses

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Laser-induced periodic surface structures (LIPSS or ripples) can be found on surfaces of metals, dielectrics and semiconductor materials processed with single and multiple ultrashort (femtosecond and picosecond) laser pulses. Although these structures are known for more than 50 years, the underlying physical mechanisms of the pattern formation are still a topic of intensive discussions. There are two main approaches to the problem of LIPSS formation. The most frequently-cited mechanism is attributed to the interference between the incident laser light and the surface-scattered electromagnetic waves, which manifests itself in a periodically-modulated temperature of free electrons and lattice in the surface layer. Another mechanism involves development of hydrodynamic instabilities in a thin molten layer on the irradiated surface. However, a combined action of these two mechanisms seems to be also possible.

High-power ultrashort-pulse lasers enable effective generation of higher harmonics of periodic structures, which can be used to shed a new light on the LIPSS formation mechanisms. Here we report our experimental results on the LIPSS formation with Lumera Rapid 40 W picosecond laser system at different wavelengths of the incident laser light. The experimentally measured pattern period is compared with the theoretical predictions made in the frames of the surface-scattered wave theory and numerical simulations of the laser-induced heating dynamics. Structures induced by single and multiple pulses are compared. Estimations made on the basis of development criteria for different hydrodynamic instabilities allow us to sort out the most probable mechanisms, that can bridge the gap between the sample temperature evolution and the surface profile formation.

WS100-7, Session 2

The role of metastable state molecules in air ionization by high-peak-power laser pulses

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The interaction of ultrashort powerful laser pulses with gaseous media is a complex phenomenon. Depending on the laser intensity and peak power, several physical mechanisms can be involved in affecting the transmitted energy of the pulse and its temporal and spatial profile. These effects include multiphoton and tunnel ionization of ambient gas, Kerr induced self-lensing, self –induced plasma defocusing and self-phase modulation [1, 2]. Since the majority of laser micro-processing is performed in gases, mainly in air at atmospheric conditions, it is mandatory to understand how the atmospheric plasma may affect the pulse propagation.
Previous studies have shown that the presence of a gas environment in microprocessing can lead to higher target absorptivity [3] and ultradeep crater formation [4, 5] due to radiative effects of ablation and air induced plasmas.

In this talk we will report evidence of accumulation effects upon propagation of focused fs laser pulses (800 nm, 120 fs) in air. For multi-pulse material processing, the accumulation effects facilitate multiphoton ionization of air by subsequent laser pulses thus strongly affecting the pulse energy transmitted through the focal region of the laser beam. The transmission measurements have been carried out in air at different pressures and in vacuum for comparison. We have also performed spectroscopic measurements in the air breakdown plasma which show that molecular nitrogen lines starts to appear at fluences well below the breakdown threshold determined from the transmission measurements. The plasma absorption effects are found to be dependent on the pulse repetition rate and are considerably stronger at 1 kHz as compared to 1 - 10 Hz. This suggests that metastable-state air molecules play an important role in initiation of air breakdown at high repetition rates. The spectroscopic data indicate that the ionization process involves a metastable state of molecular nitrogen with a life time of about 10 ms. Modelling of laser-induced air ionization using the model [5] shows good agreement with the experimental data. The role of plasma absorption in material processing with high rep-rate and burst mode lasers will be discussed.

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WS100-8, Session 2

Plasma physics of inertial fusion: a novel approach

Robert Bingham, STFC Rutherford Appleton Lab. (United Kingdom)

No Abstract Available

WS100-9, Session 3

4-mJ, 50-kHz picosecond pulses from PERLA C thin-disk laser platform

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In this contribution, we present a high-repetition-rate, kW-level picosecond Yb:YAG thin-disk laser system PERLA C developed at the HiLASE Center. Its design is based on the CPA (Chirped Pulse Amplification) technique, comprising a low-energy Yb-fiber front-end, a chirped volume Bragg grating (CVBG) stretcher, two thin-disk regenerative amplifiers and a CVBG compressor. This system's target parameters are 5-mJ pulse energy at 100 kHz repetition rate (500 W average power) and pulse duration below 2 ps, with possibility to adjust the repetition rate of the system from 50 kHz to 1 MHz.

Each amplifier uses one diamond-bonded Yb:YAG thin disk (10 mm in diameter, 220 μm in thickness, 7.2 at.% doping concentration). To reduce thermal load, the thin disks are zero-phonon-line pumped at 969 nm. The first-stage amplifier includes a nearly 3 m long standing-wave cavity with pump spot diameter of 2.8 mm (0.5-kW pump diode laser) and a home-made water-cooled, dual BBO crystal Pockels cell for fast switching of the system (approximately 15 ns rise and fall time). The maximum extracted pulse energy from this amplifier was 1.2 mJ (average output power of 120 W) at pump power of 430 W in a nearly diffraction-limited beam (M2 ≈ 1.4). Compressed pulses from the CVBG compressor (efficiency 85%) had duration of 1.3 ps and spectral bandwidth of 1.3 nm (FWHM).

Part of the uncompressed output of this regenerative amplifier (around 20 W) is used for seeding the second-stage amplifier. This stage is based on a 6.5 m long ring cavity with two V-passes through the thin disk and 5.2-mm pump spot. It is pumped with 2.2-kW CW fiber-coupled diode laser and contains a Pockels cell with two 10?10?25 mm3 BBO crystals in home-made holders enabling 10-kV, 1-MHz operation. The optical layout of the amplifier is compact with a footprint size of less than 1000?600 mm2.

In continuous-wave operation, the maximum output power obtained from this setup was 565 W at 1.21 kW pump power in the fundamental transverse mode, which gives optical-to-optical efficiency of 47%. In pulsed operation with seed pulse energy of 0.2 mJ, 4-mJ pulses at 100 kHz (400 W average output power) were generated with extraction efficiency of 43%. Recently, we used this system for an industrial application requiring tuning of the repetition rate down to 50 kHz and doubling pulse energy. In this regime, average output power of 250 W (5 mJ) was achieved. Compressed pulses had duration of 1.8 ps and energy of 4 mJ, i.e. the compression efficiency achieved with the CVBG compressor was 80%.

Compressor efficiency and temporal chirp are being optimized and achieved results will be presented. As the final parameters are being approached, our current work is also focused on obtaining the targeted 5 mJ/100 kHz output from the laser system.

WS100-10, Session 3

1 kW operation of the HiLASE slab laser system

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No Abstract Available

WS100-11, Session 3

Extension of application potential of a picosecond 100 kHz high-average power Yb:YAG thin-disk laser by harmonic generation into VIS, UV, and DUV

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High average power diode pumped solid state lasers based on Yb:YAG gain medium, which are nowadays offering picosecond pulses in high quality beams, are becoming mature. They are used for scientific applications and increasingly often in industrial ones. On the other hand, their inherent wavelength of 1030 nm is not optimal or even usable for many laser-matter interactions. The wavelength conversion of the fundamental beam can solve the demand for other wavelengths. The most straightforward approach of extending the wavelengths is harmonic

generation. We will present generation of four other harmonic frequencies of the high average power laser Perla-C developed at the HiLASE Centre. We cover all harmonics that are achievable by second order nonlinear optical conversion in commercially available solid state crystals. This significantly increases the application potential of the developed laser. The fundamental wavelength of 1030 nm is produced by the Perla-C laser based on the chirped-pulse amplification of sub-ps oscillator pulses in two regenerative amplifiers where the active medium of Yb-YAG is in the form of the thin disk. The diode pumping at zero phonon line wavelength increases the amplifier efficiency and decreases the thermal load on the thin disk. The spatial mode of the output beam is close to fundamental. The repetition rate is 100 kHz and the pulses are of 1-4 ps duration. The pulse energy is 1 mJ from the first regenerative amplifier and 2 mJ from the second. Conversion into four different wavelength follows. The fundamental infrared beam is first frequency doubled in an LBO crystal, Type I phase-matching. The rest of the fundamental and the generated second harmonic (515 nm) are frequency summed in BBO or LBO (Type II) crystals for the third harmonic production at 343 nm. If the fourth harmonic instead of the third one is demanded by our users, the second harmonic beam is again frequency doubled in BBO or CLBO crystals (Type I) and deep UV radiation on 257.5 nm is generated. The unconverted fundamental beam is further summed with the fourth harmonic in BBO or CLBO crystals (Type I) and the fifth harmonic (206 nm) is produced. The issues related to high average power harmonic generation for the picosecond pulse duration will be addressed. The latest results on the harmonics generation will be presented. Coverage of these harmonics is unique for high average power picosecond laser systems. All five harmonics are at a disposal for users and the particular properties of the pulses, i.e. ultrashort duration and good optical quality of the beams, have been used in material processing of which some special applications, such as surface structuring, will be presented. Various wavelengths enable study and optimization of the laser-matter interaction in the dependence on the wavelength.

WS100-12, Session 3

High-energy burst pulse amplification in PERLA B thin-disk laser platform

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High-average power pulsed diode-pumped solid-state lasers operating at high repetition rates and delivering ultrashort pulses are essential in many fields of modern physics and industrial applications. Scaling of these lasers towards higher pulse energies is often limited by the onset of thermal effects which are determined by the average power. In order to achieve high pulse energies one could decrease the repetition rate, but on the other hand, too high pulse energies can be destructive for the used optics and they can induce nonlinear effects, like self-focusing or self-phase modulation.

In order to reach higher pulse energies and to keep the laser system safe, the burst pulse amplification can be applied. Recent progress in the development of burst-mode lasers have led to raise of the burst duration to millisecond range, pulse energy up to 1 J per pulse in single shot systems and pulse durations below nanosecond.

In this paper we would like to propose a way of increasing the pulse energies by operating the PERLA B laser in 100 Hz burst mode. The CPA-based system consists of a fiber front-end, Yb:YAG thin-disk regenerative amplifier operating at 10 kHz repetition rate delivering up to 10 mJ per pulse, followed by the multipass Yb:YAG thin-disk amplifier boosting the burst energy to 0.5 J level and a grating compressor for sub-picosecond pulses. The concept of the thin-disk technology allows for energy and power scaling with high efficiency. However due to small single pass gain a multi-pass scheme with precise mode matching is required for efficient energy extraction. We evaluated the thin disk AE by measuring surface temperature and single pass gain in CW and pulsed pumping for pump spot diameters of 2.1 mm, 3.2mm and 4.2mm, pump pulse widths of 1ms, 1.5ms and 2ms, in case of pulsed pumping.

Since output from thin disk amplifier is limited by the onset of ASE effects, we are developing an analytical model to estimate the influence of ASE on amplifier performance. This model estimates the key parameters of amplifier such as pre-pumping time, number of passes on thin disk, AE and maximum extractable energy. Moreover, scaling limits imposed by ASE and thermal effects will be analysed. The outcomes from the analytical modelling along with the detailed experimental results will be presented.

WS100-13, Session 3

Targetry solutions for high-repetition rate lasers

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No Abstract Available

WS100-14, Session 4

Wavelength tunable parametric mid-IR source pumped by a high-power picosecond thin-disk laser

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Mid-IR wavelength range offers interesting applications in gas sensing, medicine, defense, material processing, and others. Many processes are dependent on wavelength and a wavelength tunable mid-IR source would enable useful tool for optimization of the laser-matter interaction. Further, the use of higher average power sources enables increase in processing speed. The high average power wavelength tunable mid-IR source can be achieved by optical parametric conversion if a high average power pump laser of high quality beam is available. Very low absorption of nonlinear crystals ensures low thermal load at high average power.

We have developed picosecond 100 W laser operating at repetition rate of 100 kHz and wavelength of 1030 nm. The laser is used to pump mid-IR optical parametric generator and amplifier. Picosecond pulses of a mode-locked fiber oscillator operated at wavelength of 1030 nm are stretched in a chirped volume Bragg grating (CVBG) up to 500 ps. This seed beam is amplified in Yb-doped fibers and is sent into 100-kHz regenerative amplifier based on Yb:YAG thin-disk and Pockels cell with BBO crystal. The heat load of the thin disk is effectively reduced by the zero-phonon line pumping by laser diodes at 969 nm. The regenerative amplifier delivers output power up to 120 W, which is compressed by the CVBG with 80 % transmission below 2 ps.

We are developing a ten watt level picosecond mid-IR source pumped by a beam of the high average power picosecond laser system. Part of the beam pumps optical parametric generator (OPG) consisting of a 10-mm long PPLN. The PPLN crystal can be seeded by a continuous wave laser diode at 1.94 μm, which is normally used for the alignment of the signal beam. The seeding of the OPG stage by continuous-wave laser diode determines the signal and idler wavelength to 1.94 μm and 2.2 μm, respectively. Further, it decreases the generation threshold and increases the power of the generated signal. Typical OPG output is about 70 mW for 1.6 W pumping in the seeded operation. If the OPG stage is unseeded, the signal and idler spectrum is much broader and the measured power is about 25 mW. The signal pulse energy is further boosted in an optical parametric amplifier (OPA) consisting of two walk-off compensated KTP crystals. For pumping of 42 W the 7 W in signal beam was achieved at wavelength of 1.94 μm, i.e. for seeded OPG stage. The estimated power of the corresponding 2.2 μm idler beam was 6 W. We tested the wavelength tuning of the OPA stage for the unseeded OPG stage. The idler beam was tuned between 2.18 μm and 2.4 μm with typical bandwidth of 10 nm.

Further increase in the pump intensity is planned and more than 10 W in the idler beam is expected. The increase in the idler wavelength tuning up to 3 μm is planned. The latest measurements of amplification and beam characteristics will be presented. The possibilities of generation of even longer wavelength will be discussed.

WS100-15, Session 4

Design of a telescopic zoom system for electron acceleration

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In this paper we are describing a telescopic zoom system that has been designed for the purpose of electron acceleration. The system will be tested in the Apollon facility currently under construction in France [1]. Apollon laser system will be delivering 4 beams: one 10 PW beam (F1 beam 400 mm diameter), one 1 PW beam (F2 beam 140 mm diameter) and two additional probe beams (F3 and F4) at a repetition rate of 1 shot per minute. The laser system is based on Ti-sapphire amplifiers pumped by frequency doubled solid-state lasers. Although the main 10 PW beam is designed with an expected 150 J/15 fs after compression, we have already achieved 30 J uncompressed than will be the first stage F2 beam once compressed. Details about this design and the performance level will be presented at the same conference [2].

The telescope is made of two spherical mirrors and its design follows the general arrangement for inverse cassegrainian systems described by Rosin [3]. Following a general algebraic theory based on first and third order equations, it is possible to find a system corrected for spherical aberration, coma and astigmatism such that a collimated input beam will be focused to a perfect focal spot like in the Schwarzschild system [4]. We will show that apart from the afocal solution, it is possible to get a continuous range of focal lengths when changing the distance between the two spherical mirrors. As a practical example and assuming the primary mirror radius equals 10 m, a moderate mirror distance change (<5m) gives a large focal length change (from 2.5 to 50 m). Based on the aforementioned conditions and including alignment margins, we can assess the mirror sizes for Apollon's F2 and F1 beamlines: primary mirror size will be 420 mm for F2 (respectively 1160 mm for F1) and secondary mirror size will be 160 mm for F2 (respectively 420 mm for F1). Of course, the system is no longer compensated for spherical aberration, coma and astigmatism and we will show how these aberrations will be evolving when using the full zoom range.

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WS100-16, Session 4

High-repetition-rate few-cycle laser for attosecond pulse generation at ELI-ALPS

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The Extreme Light Infrastructure (ELI) is currently being installed in several European countries aiming to provide unique user facilities with beyond state-of-the-art laser systems. The attosecond facility ELI-ALPS in Szeged, for example, will host several laser systems that will be used for attosecond pulse generation at unprecedented pulse parameters (energy and repetition rate). One of the laser systems is the HR (high repetition rate) laser that targets pulse parameters of 1mJ, 6fs pulses at 100 kHz repetition rate (100 W average power) and with CEP stable operation in its first implementation phase. In its final stage, the second phase, the HR laser will deliver up to 5 mJ of energy corresponding to 500 W of average power.

The first phase of the laser system is based on a two-stage nonlinear compression approach of a fiber chirped-pulse amplifier that has shown promising scaling aspects, in particular, with respect to average power. This proved to be an important milestone, because the required average power of 100 W for few-cycle pulses is challenging to achieve with the commonly used OPCPA systems. The approach builds on a 3 mJ, 300 W, 100 kHz femtosecond fiber-chirped pulse amplification system, which utilizes coherent combination of 8 main-amplifier channels to achieve this unique performance level. The frontend of the whole amplifier chain is a passively stabilized 80 MHz oscillator (Toptica Photonics) with excellent CEP stability of less than 100 mrad. The CPA system has been extensively tested over the last months and has shown excellent stability values in terms of average power stability, pulse-to-pulse stability, pointing stability and excellent repeatability. After a short warm-up time of a few minutes the system runs for several hours and has been tested for continuous operation times of up to 24 hours. This system is followed by two noble-gas-filled capillaries each with an inner diameter of 250 μm. In the first stage spectral broadening in the capillary and subsequent compression yields 30 fs pulses that are further down-compressed to <7fs in the second compression stage. Due to the excellent beam quality of the fiber CPA system this two-stage approach reaches a throughput efficiency on the order of 40%. In its current implementation status the nonlinear compression has been operated at up to 0.75mJ, sub<7fs and 75 W of average power. This performance has been maintained up to 24 hours proving the excellent reliability of the complete system.

We will show detailed measurements and characterization of the CPA system as well as the compression unit. General scaling properties of hollow fiber compressors, with emphasis on average power related aspects, as well as recent progress towards the achievement of the final target parameters of 1mJ, 6fs will be discussed. Furthermore, a detailed discussion on the CEP stabilization of the system will be given and supported by the latest measurement results using a stereo ATI device. This will be accompanied by a description of energy scaling possibilities even beyond the current target parameters.

WS100-17, Session 4

100-W 1-MHz operating Yb-rod fiber front-end for seeding of a 1-kW thin-disk amplifier

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State-of-the-art industrial and biotechnological laser applications like highly precise cutting and drilling of hard to process materials, generation of long-wave infrared radiation, or design of extreme UV and soft X-ray radiation laser produced plasma sources for semiconductor litography require reliable high repetition rate kW-class picosecond lasers emitting in 1-um spectral region. A promising approach to generation of such pulses seems to be utilization of a thin disk-based power amplifier seeded by a powerful fiber laser system. Such a combination enables to design a compact and robust picosecond laser exceeding 1-kW of average output power. We propose a 1-MHz repetition rate-operating 100-W Yb-doped fibre-laser-system followed by an Yb:YAG thin-disk-based multipass amplifier targeted as a pre-pulse laser for laser produced plasma generation. In this talk we present a conceptual scheme of the system with emphasis on design and results obtained after construction of the 100-W seed fiber laser.

The system is based on a CPA concept, i.e. the pulses are stretched in time, amplified, and will be compressed again bellow 2-ps pulse length. The system therefore consists of an oscillator, a chirped fiber Bragg grating (CFBG) based pulse-stretcher, a pulse picker, several stages of Yb-doped fiber preamplifiers as well as a photonic-crystal fibre pre-amplification stage and an Yb rod amplifier as a power amplifier. Output pulse with 100-uJ of pulse energy are planned to be boosted by a single stage diode-pumped Yb:YAG thin disk amplifier to 1-mJ at 1-MHz repetition rate. We expect to employ a single diamond-bonded disk in multipass configuration. The amplified pulse should be compressed by a compact double-pass chirped volume Bragg grating (CVBG) pulse compressor with diffraction efficiency reaching up to 92 %.

At this moment the system of preamplifiers is being assembled. An all-normal-dispersion in-house developed oscillator (ANDi-type) delivers 3-ps long chirped pulses at 48-MHz repetition rate with 20-nm bandwidth so the pulses are compressible bellow 100-fs. Average output power is approximately 70-mW and pulse energy 1.5-nJ. Pulses are stretched to roughly 1-ns and amplified in a dual stage preamplifier with 30-cm of Yb-doped fiber to 100-mW (2.1-nJ pulse energy). Pulse repetition rate is decreased to 1-MHz using an acousto optical modulator (AOM) and amplified again to 500-mW (0.5-uJ pulse energy) of average power in a 40-cm long SM Yb-doped fiber. Following chain of two LMA double clad fibers (10- and 40-um core diameter, respectively) allows reaching of several Watts of output power and pulse energy of several uJ. The output is finally launched into the power amplifier consisting of a 80-cm long Yb-rod. Assembling of all fiber amplifiers is expected by the end of this year and the latest results will be presented by the time of the conference.