SPIE®

2013 Optics+ Optoelectronics

15-18 April 2013

Technical Summaries

www.spie.org/oo

Location
Clarion Congress Hotel
Prague, Czech Republic

Conference
15-18 April 2013

Exhibition
16-17 April 2013

2013 Optics+ Optoelectronics



General Chairs:

Jiri Homola
Institute of Photonics and Electronics of the ASCR, v.v.i., Czech Republic

Chris Edwards
Central Laser Facility, Science and Technology Facilities Council, United Kingdom

Mike Dunne
Lawrence Livermore National Lab., United States

Ivo Rendina
CNR/Istituto per la Microelettronica e Microsistemi, Italy

Honorary Chair:

Miroslav Miler
Institute of Photonics and Electronics of the ASCR, v.v.i., Czech Republic

Click on the Conference Title to be sent to that page

Contents

Co-Sponsoring Organisation:
AMERICAN ELEMENTS®

Co-Operating Organisations:
HiPER eli beamlines
ICO International Commission for Optics / Commission Internationale d'Optique

Promotional Partner:
Electro Optics Magazine

8771-1, Session 1

High contrast composites with unusual elastodynamic properties *(Invited Paper)*

Graeme Milton, The Univ. of Utah (United States)

Metamaterials can have an interesting elastodynamic behavior. Their effective mass density can be anisotropic, negative, or even complex. Even the eigenvectors of the effective mass density tensor can vary with frequency. Within the framework of linear elasticity, internal masses can cause the effective elasticity tensor to be frequency dependent, yet not contribute at all to the effective mass density at any frequency. One may use coordinate transformations of the elastodynamic equations to get novel unexpected behavior. A classical propagating wave can have a strange behavior in the new abstract coordinate system. However the problem becomes to find metamaterials which realize the behavior in the new coordinate system. This can be solved at a discrete level, by replacing the original elastic material with a network of masses and springs and then applying transformations to this network. The realization of the transformed network requires a new type of spring, which we call a torque spring. The forces at the end of the torque spring are equal and opposite but not aligned with the line joining the spring ends. We show how torque springs can theoretically be realized.

8771-2, Session 1

On the feasibility of a 2D acoustic cloak using layers of elastic materials

Frank Simon, Cécile Dutrion, ONERA (France)

For a few years, researchers have been investigating the possibility of making an acoustic cloak using metamaterials. One popular approach consists in creating a material having the effective properties of the theoretical anisotropic fluid described by Cummer [1] and leading to perfect cloaking. This follows an analogous result in electromagnetism where it is demonstrated that the strong anisotropy of the corresponding electromagnetic parameters are required. Nevertheless, up to now, in practice, no such material has satisfied the constraints inherent to the theory in acoustic domain.

That is the reason why this paper examines an alternative approach, ie the feasibility of a 2D acoustic cloak with layers of elastic materials surrounding an infinite rigid cylinder submitted to normal plane waves. To do this, a semi-analytical code has been written to calculate the pressure field around a cylinder surrounded by a multilayered orthotropic elastic coating. The scattered pressure field, which is to be minimized, depends on the mechanical and dimensional characteristics of elastic layers. Since the number of parameters rapidly increases with the number of layers, it has been necessary to restrict the study.

The coupling of a genetic algorithm and DACE (Design and Analysis of Computer Experiments) methods with the vibro-acoustic code showed that a very good scattering reduction could be achieved with only 2 layers: the exterior one being isotropic and stiff, the interior one being orthotropic and soft. A numerical application is led with a rigid cylinder 26.6 cm in diameter placed in air. Although the best results (up to 96% scattering reduction in comparison with the uncloaked case) do not correspond to realistic configurations, further investigations limited to existing materials demonstrated that a substantial reduction could nevertheless be expected. So, the scattering cross-section around the cylinder can be cut by half using an internal 10 mm thick layer of orthotropic polyurethane foam and a thin external isotropic layer corresponding to some polymers or woods. According to simulations, the scattering reduction occurs in a narrow frequency band around 500-600Hz, depending on the material chosen for the external layer. However, experiments are to be conducted in order to validate these numerical results.

[1] S. Cummer, D. Schurig, One path to acoustic cloaking, New Journal of Physics, 9, 45, 2007

8771-3, Session 1

Mechanically tunable terahertz metamaterials

Charan M. Shah, RMIT Univ. (Australia); Jining Li, Withawat Withayachumnankul, Benjamin S. Ung, The Univ. of Adelaide (Australia); Arnan Mitchell, Sharath Sriram, Madhu Bhaskaran, RMIT Univ. (Australia); Sheng-Jiang Chang, Nankai Univ. (China); Derek Abbott, The Univ. of Adelaide (Australia) and RMIT Univ. (Australia)

Metamaterials are artificial composites consisting of array of periodic sub-wavelength resonator structures. They can modify the electromagnetic waves in unique ways not achieved by naturally occurring materials. Until now most of the metamaterials functionality is demonstrated within a narrow spectral frequency range. However, in many cases it would be desirable to adapt the metamaterial to its environment by tuning its frequency. In this work, the electromagnetic resonance of the metamaterials is controlled by substrate deformation. Further, the resonance Q factor of metamaterials is improved by integrating an interdigitated structure to the design.

The metamaterials fabricated on a flexible substrate modifies the inter-cell capacitance when mechanically strained, and hence shifts the resonance frequency of resonators. Electromagnetic device design and flexible electronics fabrication techniques are combined to demonstrate such mechanically tunable metamaterials operating at terahertz frequencies. Two different I-shaped resonator design, with and without interdigitated structure is studied. The I-1 design (without interdigitated structure) and I-2 design (with interdigitated structure) are comprised of a planar array of resonators micro-fabricated on a highly elastic polydimethylsiloxane (PDMS) substrate. These resonator designs were simulated and experimentally verified for uniaxially stretching.

When the resonators where mechanically strained, the I-1 design resonator shows a resonance frequency shift of 30 GHz, whereas the I-2 design with interdigitated structure shows a further improvement of resonance frequency shift by 10% (upto 40 GHz). The I-2 design exhibits higher sensitivity to applied mechanical strain compared to the I-1 design. The robustness of the fabricated metmaterials was verified by repeated stretching and relaxing cycles. In our experiment greater than 8% of the tuning range was achieved with good repeatability. A large continuous tunabality of the frequency can be achieved by utilizing resonant structures on elastomeric substrates. This study promises applications of elastomeric metamaterials in remote strain sensing and other mechanically controllable metamaterial-based devices.

8771-4, Session 1

Effective index engineering in hybrid metamaterials on SOI waveguides

Natalia Dubrovina, Xavier Le Roux, Institut d'Électronique Fondamentale (France); Sylvain Blaize, Institut Charles Delaunay (France); André de Lustrac, Institut d'Électronique Fondamentale (France); Gilles Lérondel, Univ. de Technologie Troyes (France); Anatole Lupu, Institut d'Électronique Fondamentale (France) and CNRS (France)

We report experimental and modeling results for the behavior of metallic metamaterials (MMs) in a guided wave configuration aimed to explore their potential for silicon photonics applications in the near-infrared (?=1.5µm). The pursued approach consists in using a hybrid guiding structure made of metamaterial layer over a high index slab waveguide, as for instance silicon on insulator (SOI) in the present case. In such a configuration only the evanescent tail interacts with the MMs layer which acts essentially as a perturbation. Its role is to modify the effective index of the composite waveguide structure. The advantage of such a solution is to significantly reduce the propagation losses since the main part of the electromagnetic energy do not interact directly with the metallic part of the metamaterial. Our numerical simulations show that an array of gold coupled cut wires

over a slab waveguide leads to a significant variation of the slab effective index in the vicinity of the resonance [1-3]. The experimental results for the MM resonance behavior are found to be in a good agreement with modeling. It is namely demonstrated that the effective index and the loss level in such hybrid waveguides can be carefully controlled with planar metallo-dielectric MMs, paving thus the way for new optical functionalities. The ability to control the energy flow in a silicon waveguide based on the interaction of the evanescent tail with the MMs layer constitutes a real opportunity to design a novel class of photonic devices.

Acknowledgements

This work was supported by the French National Research Agency (ANR Metaphotonique, contract number 7452RA09) and the Champagne-Ardenne region.

References

[1] N. Dubrovina, L. Le Cunff, N. Burokur, R. Ghasemi, A. Degiron, A. De Lustrac, A. Vial, G. Lerondel, and A. Lupu, “Single metafilm effective medium behavior in optical domain: Maxwell-Garnett approximation and beyond,” accepted Applied Physics A (2012).

[2] A. Lupu, N. Dubrovina, R. Ghasemi, A. Degiron, and A. de Lustrac, “Metal-dielectric metamaterials for guided wave silicon photonics,” Opt. Express 19, 24746-24761 (2011).

[3] A. Lupu, N. Dubrovina, R. Ghasemi, A. Degiron, A. de Lustrac, “Metal-dielectric metamaterials for guided optics applications,” Proc. SPIE 8423, 842306 (2012).

8771-5, Session 2

Recent progress in radiative heat transfer at the nanoscale *(Invited Paper)*

Jean-Jacques Greffet, Lab. Charles Fabry (France)

Abstract Radiative heat transfer at the nanoscale can exceed Stefan-Boltzmann law by several orders of magnitude. Recent experimental and theoretical progress in the study of heat transfer at the nanoscale mediated by surface waves will be presented. Future directions using metamaterials will be discussed.

Radiative heat transfer at the nanoscale between two plane parallel surfaces can be enhanced by several orders of magnitude in the near field compared with Stefan’s law. While this effect has been first observed experimentally in the 60’s at low temperatures [1-3], it is only recently that a quantitative comparison with theory has been reported by several groups experimentally [4-6]. While the first experiments were reported for metallic surfaces, in the new generation of experiments, the flux is enhanced by the presence of surface phonon-polaritons as suggested in ref. [7]. In this communication, I will present a new perspective on heat transfer at the nanoscale inspired by the Landauer formalism developed for electron transport in mesoscopic physics. This proviides a convenient framework to discuss the maximum flux. In the second part, I will review recent advances in this rapidly gexpanding field.

The maximum possible flux in the near field was first estimated by Pendry [8]. Following his approach, the heat transfer exchanged between two surfaces has been recast using a Landauer form [9]. This formulation turns out to be very convenient to analyse the physical mechanisms involved in the enhanced heat transfer at the nanoscale. The flux appears to be the sum of different modes characterized by their wavevector. Three different types of modes are identified : i) modes propagating in a vacuum gap corresponding to Stefan’s law with a parallel wavevector smaller than ?/c , ii) modes propagating in the substrate but totally reflected at the dielectric-air interface, iii) surface modes with a parallel wavevector larger than n?/c. Each mode contributes to a heat transfer proportional to the thermal quantum of conductance.

Finally, it has been recently proposed to modulate the heat transfer by perturbing the optical properties of the media using phase change materials [10]. These new concepts will be presented. I will also discuss the role of textured surfaces and recent experiments with graphene.

REFERENCES

1. E. G. Cravalho, C. L. Tien, and R. P. Caren. J. Heat Transfer Vol. 89, 351 (1967).

2. Hargreaves, C.M. Anomalous radiative transfer between closely-spaced bodies. Phys. Lett. A 30, 491-492 (1969).

3 Domoto, G.A., Boehm, R.F., Tien, C.L. Experimental investigation of radiative transfer between metallic surfaces at cryogenic temperatures. J. Heat Transfer 92, 412 (1970).

4. S. Shen, A. Narayanaswamy, and G. Chen. Nano Lett. 9, 2909 (2009).

5. E. Rousseau, A. Siria, G. Jourdan, S. Volz, J. Chevrier, and J.-J. Greffet,

Nat. Photonics 3, 514 (2009).

6. R.S. Ottens et al. Phys.Rev.Lett. 107, 014301 (2011).

7. Mulet, J.P et al. Appl.Phys.Lett. 78, 2931-2933 (2001).

8. Pendry J., J.Phys.Cond Matter 11 6621 (1999)

9. Biehs S.A., Rousseau E., JJ Greffet, Phys.Rev.Lett. 105, 234301, (2010)

10. P.J. van Zwol et al., Phys.Rev.B 83, 201404 (2011).

8771-6, Session 2

Active nanoplasmonic metamaterials: from loss-compensation to stopped-light lasing *(Invited Paper)*

Ortwin Hess, Imperial College London (United Kingdom)

New theoretical insights [1] and experimental advances [2] have shown that gain media may efficiently be integrated into the fabric of nanoplasmonic metamaterials, removing losses and allowing for ultrafast light sources on nanoscopic dimensions [3]. The talk gives an overview of recent and ongoing progress in the exciting new realm of active, gain-enhanced nanoplasmonic metamaterials [4]. On the basis of 3D Maxwell-Bloch Langevin approach [5] we report steady-state amplification [6] and ultrafast nano-lasing [3]. We also demonstrate that in a suitably designed gain-enhanced plasmonic/metamaterial heterostructure light pulses can be completely stopped at well-accessed complex-frequency zero-group-velocity points [7], leading to nanolasing via a nonlinear stopped-light process [8].

1. S. Wuestner, et al., Phys. Rev. Lett. 105, p. 127401, 2010.

2. S. Xiao, et al., Nature 466, 735, 2010.

3. S. Wuestner, et al., Phys. Rev. B 85, 201406(R), 2012.

4. O. Hess, et al., Active nanoplasmonic metamaterials, Nature Materials 11, 573, 2012.

5. A. Pusch, et al., , ACS Nano 6, 2420, 2012.

6. J. M. Hamm, et al., Phys. Rev. Lett. 107, 167405, 2011.

7. K. L. Tsakmakidis, T. W. Pickering, J. M. Hamm, A. F. Page, and O. Hess, Light stopping and localization in plasmonic waveguides (submitted).

8. O. Hess and K. L. Tsakmakidis, Metamaterials with quantum gain, Science 339, 654, 2013.

8771-7, Session 2

Preparation and characterization of silver nanowires films for infrared radiation shielding

Concita Sibilia, Maria Cristina Larciprete, Univ. degli Studi di Roma La Sapienza (Italy)

We studied the infrared properties randomly oriented silver nanowires films deposited onto glass substrate. By definition, nanowires have cross-sectional diameters included between few to hundreds nanometers, while their lengths span from hundreds of nanometres to some hundreds microns. In recent times, several types of metallic nanowires have been extensively investigated and employed for different applications ranging from plasmonics [1] to nonlinear optics [2] and manipulation of IR radiation [3] to name some.

Two different types of nanowires were investigated, their geometrical parameters ranging form 10 to 50 nm diameters and 10 to 30 ?m lengths. Several films of silver nanowires were realized by drop casting and the infrared emission of the obtained films was characterized in the long infrared range, i.e. 8-12 microns, by observing their temperature evolution under heating regime (maximum applied temperature ~90°) with a focal plane array (FPA) infrared camera. A complete set of infrared images was recorded by placing the samples in direct contact with the heating holder and by acquiring consecutive images, during both heating and cooling processes, with a fixed time step. In particular, under the same heating conditions, the apparent temperature of the silver nanowires films, although qualitatively following the trend of the corresponding heating source temperature, show an apparent temperatures always somewhat lower. Experimental results show that the infrared emission from a mesh composed of silver nanowires might be tailored by setting different metal content, i.e. the metal filling factor.

Experimental curves were interpreted using the real and imaginary refractive index retrieved from a theoretical model, where the complex electrical permittivity results from the calculations of effective permittivities of in-plane randomly oriented metallic wires as a function of metal filling factor. The reconstructed corresponding absorbance spectra, suggest that these coatings are suitable for infrared signature reduction applications.

[1] Y.Sun, “Silver nanowires - unique templates for functional nanostructures”, Nanoscale 2, 1626 (2010).

[2] A.Belardini, M.C.Larciprete, M.Centini, E.Fazio, C.Sibilia, D.Chiappe, C.Martella, A.Toma, M.Giordano, F.Buatier de Mongeot, “Circular Dichroism in the Optical Second-Harmonic Emission of Curved Gold Metal Nanowires”, Physical Review Letters 107, 257401 (2011).

[3] M. C. Larciprete, A. Albertoni, A. Belardini, G. Leahu, R. Li Voti, F. Mura, C. Sibilia, I. Nefedov, I. V. Anoshkin, E. I. Kauppinen, and A. G. Nasibulin, “Infrared properties of randomly oriented silver nanowires”, J. Appl. Phys. 112, 083503 (2012).

8771-8, Session 2

Plasmon-mediated Smith-Purcell emission

Naoki Yamamoto, M. Kato, Tokyo Institute of Technology (Japan); F. Javier García de Abajo, Viktor Myroshnychenko, Consejo Superior de Investigaciones Científicas (Spain)

Smith-Purcell radiation (SPR) is generated in a wide wavelength range when a charged particle propagates close to a metal surface with a grating structure. The wavelength of SPR continuously changes with emission angle, so it is potentially application as a tunable light source over a broad UV to THz frequency range. In the present work the interaction between SPR radiation and surface-plasmon-polariton (SPP) induced radiation from plasmonic crystals in the optical region was investigated experimentally by cathodoluminescence microscopy performed on a 200 keV-STEM. Intensity modulation of the Smith-Purcell radiation along the dispersion lines was observed in the angle-resolved spectral images. This modulation, which occurs near the crossing points between the dispersion lines of the SPR and SPPs of the plasmonic crystal, is arising from coherent interaction between SPR radiation and SPPs, leading to characteristic Fano profiles. The interaction distance needed to excite SPR was obtained from spectral images taken by scanning the electron beam across the grating surface in an aloof configuration. Our boundary-element-method calculations show dispersion patterns in good agreement with experimental, and fully supporting the interference model noted above. This unique combination of STEM cathodoluminescence and SPR is providing direct insight into the coupling of SPPs on gratings and freely propagating light.

8771-9, Session 2

Funneling of light in combinations of metal-insulator-metal resonators

Patrick Bouchon, Charlie Koechlin, ONERA (France); Paul Chevalier, ONERA (France) and Lab. de Photonique et de Nanostructures (France); Fabrice Pardo, Jean-Luc Pelouard, Lab. de Photonique et de Nanostructures (France); Riad Haïdar, Lab. de Photonique et de Nanostructures (France) and ONERA (France)

Array of plasmonic metal-insulator-metal (MIM) resonators are known to exhibit spectrally tunable, and angularly independent nearly total absorption in strongly subwavelength volume [1,2]. Such nano-antennas are promising candidates in various applications like bio-chemical sensing, solar cells design, and photodetection.

Here, we unveil the funneling mechanism on grooves (i.e. vertical MIM) and ribbons (i.e. horizontal MIM), which is namely responsible for the redirection and subsequent concentration of the incident energy flow from the surface toward the apertures of the MIM antenna.

Thanks to the decomposition of the electromagnetic field into its propagative and evanescent parts, we unambiguously show that the funneling is not due to plasmonic waves flowing toward the apertures, but rather to the magnetoelectric interference of the incident wave with the evanescent field [2].

We experimentally demonstrate the total extinction of the reflectivity for a transverse magnetic polarized wave on a gold surface etched on 6% of its area by both narrow 150 nm and deep 2 microns grooves. These high aspect ratio metallic grooves were fabricated using a mold cast technique based on an electrolytic growth of gold. They exhibit two resonance peaks in the infrared corresponding to the first and second cavity modes inside the grooves. We also evidence the incidence-invariance of their spectral response, which undoubtedly shows the localized nature of the resonances [1].

Then, we show both theoretically and experimentally that MIM resonators can be combined within the same subwavelength period and still behave independently. This permits to conceive surface with customizable absorption, which can for instance be used in dual band absorber [3] or in omnidirectional wideband absorber [4]. An energetic analysis can also be applied on these more complex antennas geometries, which highlights a sorting effect: at each resonance wavelength, the photons are funneled towards the apertures of the corresponding MIM cavity [5]. Eventually, we will address the issue of the number of antennas which can be combined into a subwavelength period.

[1] F. Pardo el al., Physical Review Letters, 107, 093902, 2011

[2] P. Bouchon el al., Applied Physics Letters, 98, 191109, 2011

[3] C. Koechlin el al., Applied Physics Letters, 99, 241104, 2011

[4] P. Bouchon el al., Optics Letters, 37, 1038, 2012

[5] P. Chevalier et al., Journal of Nanophotonics (accepted for publication)

8771-10, Session 3

Plasmonic nanorod arrays: 3D metamaterial with hyperbolic dispersion *(Invited Paper)*

Wayne Dickson, Gregory A. Wurtz, Anatoly V. Zayats, King’s College London (United Kingdom)

Guiding and manipulating light on length scales below the diffraction limit requires structural elements with dimensions much smaller than the wavelength. Recently, novel plasmonic metamaterial has been developed based on arrays of aligned gold nanorods grown in self-assembled anodic aluminium oxide templates. This metamaterial provides a flexible platform with tuneable resonant optical properties across the visible and telecom spectral range, that can be specifically designed by changing the length, diameter and separation between the nanorods. Such metamaterials, with a controllable and engineered plasmonic response, can be used instead of conventional plasmonic metals for designing plasmonic waveguides, plasmonic crystals, label-free bio- and chemo-sensors and for development nonlinear plasmonic structures with the enhanced nonlinearities. In this talk we will overview fundamentals and applications of plasmonic plasmonic nanorod metamaterial for designing new types of nanoscale waveguides, biosensing platforms and nonlinear optical devices.

8771-11, Session 3

Bi-cell THz meta-foils

Jianfeng Wu, National Univ. of Singapore (Singapore); Herbert O. Moser, Karlsruher Institut für Technologie (Germany); Linke Jian, Agnieszka Banas, Andrew A. Bettiol, Mark Breese, National Univ. of Singapore (Singapore)

Meta-foils are all-metal, self-supported, free-standing electromagnetic metamaterials which are based on the interconnected 'S-string' architecture. In the present work, we focus on 1SE meta-foils that are characterized by having equidistant S-strings with one S-motif between successive interconnecting lines. The manufacturing of the meta-foils involves three-level lithography with precise alignment of the second and the third level and with a total of three repeated gold electroplating steps with accurate thickness control. Finally, the free-standing meta-foils are released by removing AZ resist and etching out thin Au films as well as the Cr base. The transmission spectra are measured by Fourier transform infrared spectroscopy. The spectral response of the meta-foils is characterized in the range of 2 to 8 THz. Numerical simulations are performed using the frequency domain solver of CST Microwave Studio (Computer Simulation Technology GmbH, Darmstadt, Germany), which implements a finite element method. In the simulations, the unit cell boundary condition is applied and the linearly polarized eigenwaves are directly used. For single-cell 1SE meta-foils that feature the same unit cell across the whole meta-foil area, two dominant peaks appear in the transmission spectrum. The peak at lower frequency is a left-handed magnetic resonance, and the one at higher frequency is an electrical right-handed resonance. The ability to vary their magnetic resonance properties in the terahertz regime by changing the length of the resonator unit cell is investigated here. The magnetic resonance exhibits a red shift from 4.53 THz to 2.97 THz when the resonator length is increased from 24 μm to 36 μm. Based on these results, the aim here is to study meta-foils featuring two single cells with different dimensions in the same structure to realize a bi-cell meta-foil with two distinct magnetic resonances. We will investigate how resonators of different frequency couple with each other, so determining the spectral position of resonance peaks. Here, we use equivalent circuit theory to better understand the physical nature of the coupling between resonators and, in detail, dip formation in bi-cell meta-foils. Analytical equivalent circuit theory indicates that different resonance peaks stay separated even when chosen very close. In order to further understand the performance of two individual single-cell meta-foils in a bi-cell meta-foil, we investigated the electric field distribution in bi-cell meta-foils through numerical simulation. For the electric field distribution in bi-cell meta-foils (6 μm/9 um) at the magnetic resonances. At 3.15THz and 3.83 THz, cells with 6 μm and 9 μm are strongly excited, respectively. Thus, it can be seen that in the bi-cell meta-foil the two magnetic resonances are selectively excited in either of the two single-cell sub-meta-foils. Bi-cell meta-foils provide a promising basis for the development of novel bi- and multi-frequency THz materials and devices. Although implemented here at terahertz frequencies, bi-cell meta-foils can also be extended to infrared and optical frequencies.

8771-12, Session 3

Single metafilm behavior in optical domain: the determinative role of the metamaterial resonance frequency on the effective parameters

Natalia Dubrovina, Institut d'Électronique Fondamentale (France); Petru Ghenuche, Nathalie Bardou, Lab. de Photonique et de Nanostructures (France); Shah Nawaz Burokur, André de Lustrac, Institut d'Électronique Fondamentale (France); Stéphane Collin, Lab. de Photonique et de Nanostructures (France); Gilles Lérondel, Univ. de Technologie Troyes (France); Anatole Lupu, Institut d'Électronique Fondamentale (France)

There is sustained interest for the application of metamaterials (MMs) due to their ability to exhibit unusual electromagnetic behavior, not encountered in natural materials. The engineering of such artificial materials is done generally by considering them as a bulk homogeneous media with a certain thickness and associated dielectric permittivity and magnetic permeability that can be anisotropic in the most general case. This approach proved to be valid, but essentially in the microwave domain [1]. Difficulties arise in the optical domain, in particular for the most common case of a single metafilm on a dielectric substrate. In our recent contribution [2] we shown that single metafilm behavior is indeed analogous to that of a homogeneous layer. The thickness of this layer is that of the deposited metal. The validity of this approach was verified with respect to a number of criteria consistent with the Maxwell-Garnett effective medium model.

In this communication we report new experimental and numerical modeling results further proving the validity of the Maxwell-Garnett approximation applied to a single metafilm on a dielectric substrate.

It is namely shown that in the near IR domain the most essential factor determining single metafilm effective parameters is the MMs resonance frequency. We make evidence that for a given MMs resonance frequency the normalized per surface filling factor dielectric permittivity do not depend on the filling factor, metal thickness, incidence angle and the host material in the large amount. The obtained results are explained by the variation of the MMs resonance loss factor with the frequency. The contribution of the radiative emission and the Joule heat responsible for the MMs resonance loss are discussed.

[1] X. Chen, T. M. Grzegorczyk, B. I. Wu, J. Pacheco, and J. A. Kong, "Robust method to retrieve the constitutive effective parameters of metamaterials," Phys. Rev. E 70, 016608 (2004).

[2] N. Dubrovina, L. Le Cunff, N. Burokur, R. Ghasemi, A. Degiron, A. De Lustrac, A. Vial, G. Lerondel, and A. Lupu, "Single metafilm effective medium behavior in optical domain: Maxwell-Garnett approximation and beyond," accepted Applied Physics A (2012).

8771-13, Session 3

Transformation optics and metamaterials at infrared wavelength: engineering of permittivity and permeability

Rasta Ghasemi, Aloyse Degiron, Xavier Le Roux, Anatole Lupu, André de Lustrac, Institut d'Électronique Fondamentale (France)

The transformation optics is a method of design of novel devices introduced by J. Pendry and U. Leonhardt [1,2]. In this method an initial space is transformed into a new space. And this transformed space can be materialized by a material, which the electromagnetic parameters correspond to the metric of the transformed space. In the general case the electromagnetic parameters are anisotropic tensors. At microwave frequencies these materials can be realized using classical metamaterials like SRR from J. Pendry or ELC from D. Smith [3]. At infrared wavelengths this realization is a challenge because the dimensions of the metamaterials are much smaller than the wavelength. Then the design of these metamaterials must be simplified and original methods must be developed to allow the realization of these metamaterials with controlled electromagnetic properties. In this paper we describe the realization of multilayer metamaterials working at infrared wavelength, which the permittivity and the permeability can be adjusted separately. We give some examples of realized multilayer materials operating around 150THz, with a comparison between the results of full wave simulations of these materials and their characterizations using a Fourier Transform Infrared Spectrometer. We demonstrate that the electromagnetic properties of these materials can be finely adjusted varying their geometrical parameters and the number of the layers.

8771-14, Session 3

Negative index resonant states: a route toward nonmetal plasmonics and metamaterials

Vito Mocella, Principia Dardano, Istituto per la Microelettronica e Microsistemi (Italy); Anna Chiara De Luca, Istituo di Biochimica delle Proteine (Italy); Edoardo De Tommasi, Ivo

Rendina, Silvia Romano, Istituto per la Microelettronica e Microsistemi (Italy)

Photonic crystal metamaterial can exhibit negative index properties and this behaviour is well described by a resonator model. In this work, we present the first experimental evidence that a Lorentz resonator correctly reconstruct data obtained with a negative refracting Photonic Crystal (PhC) by using a standard optical technique, such as ellipsometry. In particular we show that, in the frequency range in which the effective refractive index, neff, is equal to -1, the incident light couples efficiently to the guided modes in the top surface layer of the PhC metamaterial. These modes resemble surface plasmon polariton resonances.

In add we present measurements by using standard technique of prism coupling evanescent wave. Once again the presence of localized plasmon-like modes at the surface of a silicon two-dimensional photonic crystal slab is demonstrated.

Also in this case, in analogy with surface plasmons supported in metals in a photonic crystal metamaterial, the electromagnetic surface waves arise from a negative effective permittivity. These results opens new strategies in light control at the nanoscale, allowing on chip light manipulation in a wide frequency range and avoiding the intrinsic limits of plasmonic structures due to absorption losses in metals. Such negative index PhC materials may be of use in biosensing applications.

[1] P. Dardano, M. Gagliardi, I. Rendina1, S. Cabrini and Vito Mocella. Ellipsometric determination of permittivity in a negative index photonic crystal metamaterial. Light: Science & Applications 1, e42 (2012).

[2] G. Di Caprio, P. Dardano, G. Coppola, V. Mocella. Digital holographic microscopy characterization of superdirective beam by metamaterial . OPTICS LETTERS, vol. 37, p. 1142-1144 (2012).

[3] V. Mocella , P. Dardano, L. Moretti, I. Rendina. Influence of surface termination on negative reflection by photonic crystals". OPTICS EXPRESS, vol. 15, p. 6605-6611 (2007).

8771-15, Session 4

Nanoplasmonics: material models and computational methods *(Invited Paper)*

Kurt Busch, Humboldt-Univ. zu Berlin (Germany)

Nano-Plasmonic systems provide novel ways for controlling the propagation of light and light-matter interaction via large electric field enhancements, strong field gradients, and coupling to non-radiative plasmon modes. In view of the increasing sophistication of fabrication and spectroscopic characterization, quantitative computational approaches face challenges that go well beyond the usual description of metals as linear dispersive materials. These challenges include the development of material models that describe the (potentially) strongly nonlocal and nonlinear optical response of such metallic nano-structures as well as the strongly modified light-matter interaction that is mediated by them.

The recently developed Discontinuous-Galerkin Time-Domain (DGTD) method represents an ideal computational tool to address the above challenges. Its adaptive meshing together with high-order spatial and temporal discretization allows quantitative analyses of nano-plasmonic systems. This includes the efficient modeling of complex geometric features via curvilinear elements, the incorporation of optically anisotropic media, and the determination of electron-energy loss spectra. In addition and owing to its nature as a time-domain method, DGTD allows for the realization of advanced material models for the description of the optical properties of metallic nanostructures. For instance, a hydrodynamic description of the metal's conduction electrons, i.e. treating the conduction electron as a plasma in confined geometry that is coupled to the Maxwell allows one to capture nonlocal and nonlinear effects.

8771-16, Session 4

Dissipative optical solitons in planar meta-material cavities

Alexey Yulin, Univ. of Lisbon (Portugal); Vladimir Kuzmiak, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Sergey L. Eyderman, Univ. of Toronto (Canada)

We report theoretical results on the formation and dynamics of dissipative solitons in planar nonlinear cavities with internal resonances. The cavities are formed by two Bragg mirrors separated by a dielectric layer containing metallic nanoparticles . The structures of such a kind can be considered as planar waveguides with some cut-off frequency at which the radiation bounces between the mirrors and has zero group velocity. If the frequency of the plasmon resonance of the nanoparticles is close to the cut-off frequency then the cavity mode can interact with the resonators strongly. We assume that the resonators can also interact to each other directly through the evanescent fields. The dispersion characteristic of these systems has two branches corresponding to the mixed states of the cavity and the resonator modes. We consider the case when the dielectric layer has a conservative cubic nonlinearity. Because of the enhancement of the field in the vicinity of the nanoparticle surfaces we can assume that the plasmonic resonators are nonlinear but neglect the nonlinearity for the cavity mode. The cavity can be pumped by a laser beam through the upper semitransparent mirror. Mathematically the dynamics of the light in the cavity can be described by a system of equations for the slow varying amplitudes of the cavity mode and the resonators. We numerically found different kinds of stationary localized solutions of the equations and studied their linear stability solving the corresponding spectral problem. We also investigated the dynamics of the cavity solitons by direct numerical simulations.

8771-17, Session 4

Enhancement of the dynamic Casimir effect within a metal photonic crystal

Tsuyoshi Ueta, Jikei Medical Univ. (Japan)

If the counterposed metal plates are vibrated, when the gap between the plates becomes narrow, the energy of stationary states between the plates increases, and when it spreads, the energy decreases. Light with the energy for this energy difference arises. This is called dynamic Casimir effect.

The author has so far investigated the interaction between lattice vibration and light in a one-dimensional metal photonic crystal whose stacked components are artificially vibrated by using actuators. A simple model was numerically analyzed, and the following novel phenomena were found out. The lattice vibration generates the light of frequency which added the integral multiple of the vibration frequency to that of the incident wave and also amplifies the incident wave resonantly. On a resonance, the amplification factor increases very rapidly with the number of layers. Resonance frequencies change with the phases of lattice vibration. The amplification phenomenon was analytically discussed for low frequency of the lattice vibration and is confirmed by numerical works.

The lattice-vibrating metal photonic crystal is a system of dynamic Casimir effect connected in series, and so we can expect that a dynamic Casimir effect is enhanced by the photonic band effect.

In the present study, when an electromagnetic field between metal plates is in the ground state in a one-dimensional metal photonic crystal, the radiation of electromagnetic wave in excited states has been investigated by artificially introducing lattice vibration to the photonic crystal.

In this case as well as a dynamic Casimir effect, it has been shown that the harmonics of a ground state are generated just by vibrating a photonic crystal even without an incident wave. The dependencies of the radiating power on the number of layers and on the wavenumber of the lattice vibration are remarkable. It has found that the radiation amplitude on lower excited states is not necessarily large and radiation on specific excited levels is large.

8771-18, Session 4

Asymmetric transmission of surface plasmon polaritons

Vladimir Kuzmiak, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Alexei A. Maradudin, Univ. of California, Irvine (United States)

We describe a surface structure that possesses a different transmissivity for a surface plasmon polariton incident on it from one side of it than it has for a surface plasmon polariton incident on it from the opposite side. This asymmetric transmission of a surface plasmon polariton does not require either electrical nonlinearity or the presence of a magnetic field but is a consequence solely of the geometry of the structure. The latter was suggested to us by the structures used in recent studies of one-way diffraction gratings by Lockyear et al. [1], and of one-way propagation of acoustic waves by Li et al. [2]. To study the reflectivity and transmissivity for both the periodic and diffractive structures we used a two-dimensional elastic scattering model due to Bozhevolnyi and Coello [3]. We have demonstrated that the system consisting of a square array of scatterers deposited on a metal surface in a triangular mesh to which a diffractive structure is

added to the left side of it reveals asymmetric transmission of SPP[4]. The difference in transmittance for the left and right incidence is quantitatively described by a contrast transmissivity ratio that characterizes difference in transmittance for the left and right incidence. The mechanism for this property is related to the higher Bragg modes that are excited due to the diffractive structure.

Asymmetric transmission is demonstrated in terms of the spatial distributions of the intensity of the reflected and transmitted fields which reveals existence of the higher Bragg modes . Specifically, the diffractive structure on the opposite side supports the four lowest diffracted orders in addition to the zero order mode in the case of the right incidence, while when the structure is illuminated from the left four lowest reflected orders are excited with only a zero order in transmission.

By varying the material and geometrical parameters of the diffractive structure one can control the contrast transmission that characterizes the degree of the asymmetry.

[1] M. J. Lockyear, A. P. Hibbins, K. R. White, and J.R. Sambles, Phys. Rev. E 74 056611 (2006).

[2] X. F. Li, X. Ni, L. Feng, M. H. Lu C. He, and Y. F. Chen, Phys. Rev. Lett. 106 08430 (2011).

[3] S.I. Bozhevolnyi and V. Coello, Phys. Rev. B 58 10899 (1998).

[4] V. Kuzmiak and A. A. Maradudin, Phys. Rev. B 58 10899 (2012).

8771-19, Session 4

Metal-dielectric photonic devices for spatial filtering and image contrast enhancement

Anna Pastuszczak, Piotr Wróbel, Tomasz Stefaniuk, Marcin Stolarek, Rafal A. Kasztelanic, Rafal Kotynski, Univ. of Warsaw (Poland)

Propagation of light through layered metamaterials consisting of a metal-dielectric stack may be described as linear spatial filtering. We present the modelling and optimization strategy for engineering such metamaterials, as well as the measurement results of spatial filters consisting of titanium oxide and silver layers evaporated with PVD. Characterization of these structures includes the direct measurement of the modulation transfer function. Depending on the point spread function, the metamaterial can be applied for sub-diffraction spatial filtering or for classical spatial filtering operations. We optimize the metamaterial with respect to the shape of the complex amplitude transfer function, the average transmission coefficient and to average reflections. The shape of the point spread function can only be tailored in a limited degree, due to the limited number of the degrees of freedom contained in the structure, and only in one, planarly or radially oriented dimension. A measure of similarity obtained using the H?lder's inequality is adapted to construct a criterion function. In particular, the metamaterial's transfer function is optimized for high-pass filtering. In this case, the metamaterial consists of several substructures, each of which is an individual cavity, and is optimized by tuning the resonance order of these cavities. In this way we obtain a high transmission for a broad range of spatial frequencies. The metamaterial can be then applied to modify the contrast of the object or to introduce a phase-contrast. These structures may be used for far-field imaging. As an example, we show that they may find application as a novel phase visualization photonic elements.

8771-39, Session PS

Cyclic MAM synthesis of SPION/ BaMoO4:Er3+,Yb3+ composite and its optical properties

Chang Sung Lim, Hanseo Univ. (Korea, Republic of); Victor V. Atuchin, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation)

Multifunctional nanocomposites that exhibit significant magnetic moment and luminescence have attracted much attention because of various applications in biotechnology, medicine, and quality inspection. Superparamagnetic iron oxide nanoparticles (SPIONs) incorporated into photoluminescent composites containing two different functionalities could provide novel characteristics via the integration of fluorescent and magnetic properties, offering new potential in a wide range of applications in biomedical systems, such as targeted drugs, diagnostics, therapeutics and bio-imaging. In this study, SPIONs, incorporated Er3+-doped BaMoO4 (BaMoO4:Er3+) and Er3+/Yb3+ co-doped BaMoO4 (BaMoO4:Er3+/Yb3+) composites were synthesized by the cyclic microwave-assisted metathetic (MAM) method.

SPION/BaMoO4 :Er3+,Yb3+ composites were successfully synthesized by a cyclic MAM method. The microstructure exhibited well-defined and homogeneous morphology with BaMoO4:Er3+/Yb3+ particle sizes of 1-2 ?m and Fe3O4 particle sizes of 0.1-0.5 ?m. The Fe3O4 particles were self-preferentially crystallized and immobilized on the surface of BaMoO4:Er3+/Yb3+ particles. With excitation at 250 nm, the SPION/BaMoO4:Er3+ and SPION/BaMoO4:Er3+,Yb3+ composites exhibited PL emission in the blue wavelength range of 370-420 nm. The PL intensity of the SPION/BaMoO4:Er3+,Yb3+ was stronger than that of the SPION/BaMoO4:Er3+. The doping amounts of Er3+/ Yb3+ had an effect on the photoluminescence intensity. The Raman spectra of the synthesized BaMoO4:Er3+/Yb3+ (BMO:ErYb) particles and SPION/BaMoO4:Er3+,Yb3+ (F-BMO:ErYb) composites indicated additional peaks at both higher frequencies (505 and 390 cm-1) and lower frequencies (255 and 218 cm-1), which were attributed to the doping ions of Er3+/Yb3+. The Raman spectra proved that the doping ions of Er3+/Yb3+ can influence the structure of the host materials.

8771-40, Session PS

Design and analysis of a metasurface for supporting spoof surface plasmon polaritons (SPPs)

Charan M. Shah, RMIT Univ. (Australia); Withawat Withayachumnankul, The Univ. of Adelaide (Australia); Stephen Hanham, Stefan A. Maier, Imperial College London (United Kingdom); Madhu Bhaskaran, Sharath Sriram, Wayne S. T. Rowe, Arnan Mitchell, RMIT Univ. (Australia)

Surface plasmon polaritons (SPPs) are electromagnetic waves propagating on the interface between a metal and dielectric. Such SPPs are usually found in metals when operating at optical frequencies. The SPPs find applications in the field of biomedical sensing where they can be used to investigate an analyte near the interface. In this work we utilise a metamaterial design operating at terahertz frequencies to demonstrate that it can support such SPPs. In the absence of dielectric loss the metamaterials can provide a sharp resonance at terahertz frequencies, however, a more practical configuration requires a substrate. Hence, the effects of inclusion of polymer substrate to support spoof SPPs is also studied.

A complementary split ring resonator (CSRR) metamaterial design has been proposed to support such spoof SPPs. In our investigation, a scaled version of CSRR metamaterial design is simulated as

a periodic infinite array to obtain the transmission spectra and dispersion losses when incident by a plane wave operating at terahertz frequencies. These simulations were carried out using ANSYS HFSS full-wave electromagnetic simulator and CST Microwave studio. The metamaterial presented in this work employs simple micro-fabrication techniques to demonstrate SPPs operating at terahertz frequencies.

The CSRRs when simulated as a free standing structure demonstrates sharp resonance and their potential for supporting SPPs. From the simulation results it is observed that by addition of substrate there is a red-shift in the resonance frequency and reduction in the magnitude. This substrate effect is minimized by fabricating the CSRR on a low-loss, low refractive index and isotropic substrate like cyclic-olefin copolymer. The ability to fabricate micro-structure metamaterials on large polymer substrate sheets will allow the realization of SPP for biomedical applications. In this work we also demonstrate the fabrication method employed to fabricate CSRR structures on polymer substrate to experimentally demonstrate SPPs.

8771-41, Session PS

Preparation and characterization of Sr3V2O8 nanoparticles performed by cyclic MAS route

Chang Sung Lim, Hanseo Univ. (Korea, Republic of); Victor V. Atuchin, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation)

White light-emitting diode (LED) have been attracted as a successor of a new light source to the fluorescence and incandescent lamps. The white LED was mainly consisted of blue LED and yellow-red phosphors or ultraviolet LED and blue-green-red phosphors. Many inorganic or organic phosphors have already found for these white LED. Among various number of phosphors, metal orthovanadates have attracted considerable attention for potential applications in the broadband photoluminescence in the visible light range, as well as IR-laser, photocatalyst, ferroelectric and microwave devices. In the present study, the Sr3V2O8 nanoparticles were synthesized using a cyclic microwave-assisted solvothermal (MAS) route. The characteristics of the synthesized Sr3V2O8 nanoparticles are discussed in detail based on the MAS reaction in ethylene glycol under the high sealed pressure.

Sr3V2O8 nanoparticles were synthesized successfully using a cyclic MAS route in a hot ethylene glycol solution as a polar solvent. Well-crystallized Sr3V2O8 nanoparticles were formed after heat-treatment at 600°C for 3 h showing a fine and homogeneous morphology with particle sizes of 100-150 nm. FT-IR spectrum of the Sr3V2O8 nanoparticles showed that the large isolated absorbable peak around 820 cm-1 reveals typical characteristic of a strong V-O stretching in the [VO4]3- with a strong IR absorbable band at 920 cm-1. The strong V-O stretching peaks are contributed to the uniform regular [VO4]3- tetrahedron of the metal orthovanadates. With excitation at 250 nm Sr3V2O8 nanoparticles exhibit major PL emissions in the blue wavelength range of 420-430 nm. The Raman modes for the Sr3V2O8 nanoparticles were detected at 860, 855, 785, 396 and 329 cm-1, the free rotation mode was detected at 180 cm-1 and the external modes were localized at 146 and 127 cm-1. The well-resolved sharp peaks for the Sr3V2O8 nanoparticles indicate that the synthesized particles are highly crystallized.

8771-42, Session PS

Optical properties of a quantum dot: metal nanoparticle complex interacting with a weak probe field

Spyridon G. Kosionis, Andreas F. Terzis, Univ. of Patras (Greece); Seyed M. Sadeghi, The Univ. of Alabama in Huntsville (United States); Emmanuel Paspalakis, Univ. of Patras (Greece)

The optical properties of complex nanosystems that combine semiconductor quantum dots (SQDs) and metallic nanoparticles (MNPs) have attracted significant interest in recent years. The placement of the SQD next to a MNP leads to significant alteration of the electromagnetic field felt by the quantum systems due to the strong interaction between the excitons of the SQD and the surface plasmons of the MNP. This has significant influence on the optical properties of the hybrid complexes [1-4].

In all of these studies the optical response of the probe field is studied solely by the optical susceptibility of the SQD. Actually, it has been shown that the linear absorption spectrum of a SQD–MNP hybrid system has a Lorenzian form and its width and height is strongly dependent on the distance between the SQD and the MNP [1].

In this work we analyze the linear optical susceptibility of a SQD–MNP complex system that is comprised of a spherical MNP and a small SQD. The SQD is described by a two-level system and the interaction of the system with an external laser field is described by the modified nonlinear density matrix equations that take into account the interaction between excitons and surface plasmons [1-4]. We present approximate analytical solutions of the nonlinear density matrix equations and use these solutions for the determination of the linear optical susceptibilities of the SQD, the MNP and the total system. We find that the linear optical susceptibility of the SQD leads to an absorption spectrum that is not Lorenzian. The absorption spectrum can become zero for specific frequencies and even negative for a range of frequencies. The latter suggests that the quantum coherence generated in the SQD-MNP system can reverse the course of energy transfer as dictated by Förster energy transfer. In addition, we show that the linear susceptibility of the MNP is strongly influenced by the presence of the SQD. We find that both the SQD and the MNP susceptibilities contribute to the optical properties of the hybrid system. We investigate the dependence of the linear optical susceptibilities of the SQD, the MNP and the total system on the interparticle distance. Actually, all of these effects occur due to the strong exciton-plasmon coupling and do not need the use of additional external (coherent or incoherent) fields.

Acknowledgements

This research has been co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the Operational Program “Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF) - Research Funding Program: Archimedes III.

References

1. Z. Lu and K.-D. Zhu, J. Phys. B 42, 015502 (2009).

2. S. M. Sadeghi, Nanotechnology 21, 455401 (2010).

3. J.-B. Li, N.-C. Kim, M.-T. Cheng, L. Zhou, Z.-H. Hao, and Q.-Q. Wang, Opt. Express 20, 1856 (2012).

4. J.-J. Li and K.-D. Zhu, Phys. Rev. B 83, 245421 (2011).

8771-43, Session PS

Three-dimensional metamaterials constructed by metal stress driven method in infrared regime

Che Chin Chen, Instrument Technology Research Ctr. (Taiwan) and RIKEN (Japan); Yu Hsiang Tang, Ming Hua Shiao, Instrument Technology Research Ctr. (Taiwan); Atsushi Ishikawa, Takuo Tanaka, RIKEN (Japan); Pin Chieh Wu, National Taiwan Univ. (Taiwan); Din Ping Tsai, National Taiwan Univ. (Taiwan) and Academia Sinica (Taiwan)

In this study, we present a method to fabricate the three dimensional (3D) split-ring- resonator (SRR) based metamaterials and the corresponding experimental optical properties. The 3D structures evolved from 2D template by means of metal stresses which were developed during the 2D template formation. The fabrication processes simply combined general lithography systems and a dry etcher. The unit cell of the 2D template included two arms and a center region. The center region was design with larger width in comparison with arms and as the connection pad on the substrate. During the deposition process of Ni/Au with 10/60 nm, the intrinsic metal stresses were simultaneously developed within the metal films. Subsequent to dry etching process, the arms were released from substrate by etched away the Si substrate underneath the arms. In the meantime the arm released from Si substrate while the center region still remain on the substrate, the metal stress pulled up the arms to form 3D structures. We perform various sized 3D metamaterials by

utilizing photolithography and electron beam lithography to define 2D templates. The arm dimensions of width ranging from 100 to 200 nm/of 1?m and of length ranging from 1 to 3?m/20 to 25?m 3D metamaterials were tagged as group A/B. With the electric field of the incident light parallel to the gap of the SRRs, the transmission spectra which were extracted by FTIR spectrometer of the 3D metamaterials revealed a primary deep with wavelength of around 8 and 90 micrometers of group A and B, respectively. The high order resonances at short wavelengths were observed as well. In addition, the coupling effects of the arrayed 3D metamaterials were be further investigated by varying the spacing between the unit cells. The related resonance modes and field patterns of the 3D metamaterials will be identified through finite element method calculations by solving 3D Maxwell equations. More details will be present later.

8771-44, Session PS

Simulations of some nanomaterials having magnetic properties in the paramagnetic region

Mirela F. Nicolov, Aurel Vlaicu Univ. of Arad (Romania)

In the present study will be presented granite pegmatite class of nanomaterials. For this reason it will be done a simualtions of FeTa2O6 crystals and some other tetragonal trirutile type structure of some nanomaterials having magnetic properties. Their importance is given by their magnetic properties in the paramagnetic region. They were obtained only experimentally, and their growth form was not simulated until now, to the best of our knowledge.

In this study the growth and equilibrium forms of FeTa2O6 crystals were studied using energies in the studied nanomaterial. These energies were assumed to be directly proportional to the growth rate for the flat faces. The calculated one are {110}, {101}, {103}, {100}, {001}, {112}, {111}, and {113}. The theoretical growth forms and equilibrium forms were simulated for different values of the charges in a first classical model based on the normal charges of the O, Fe and Ta atoms whithin the structure, and in two novel models that we have introduced, which are based on the reduced charges of O, Fe and Ta.

8771-45, Session PS

Generation of less-diffractive nanoscale beam using a single aperture type plasmonic lens

Sungkyu Seo, Mohendra Roy, Korea Univ. (Korea, Republic of); Seungoh Han, Hoseo Univ. (Korea, Republic of)

A perfect lens - the simplest imaging element in optics, which can be fabricated by corrected glass that is a free of aberration, had been thought as the best solution to achieve the smallest focus in a diffraction-limited system. To realize nano-scale focusing, however, recent progresses in micro/nano device fabrication techniques provided alternatives to circumvent polishing the lens more precisely or inventing slightly better dielectric by employing sub-wavelength structures, e.g. periodic or carefully designed apertures, surface corrugations or gratings coupled with holes, which can diffract the incident light or excite and scatter surface plasmon (SP) waves more efficiently. While most of the technologies mentioned above use the SP waves that are strongly bounded to the near-field region of the metal/dielectric interface, i.e. normally within ~?/2, some research groups reported that nano-scale concentrated beam, formed by plasmonic lens(PL), can be extended to several wavelengths away from the metal surface, namely "mid-field", by careful choosing and designing of the metal or metal/dielectric structures.

In this manuscript, for the generation of less-diffractive nano-scale beam in the mid-field region, we characterize several critical parameters, i.e. material, aperture width, metal thickness, and aperture size, of the PL which contains a simple ring aperture. For the numerical analysis, we used TEMPEST, a Maxwell equations solver based on 3D FDTD(Finite-Difference-Time-Domain) simulation, and circularly polarized light of ?0=405nm incident on the fused silica side of the PL device, and firstly investigated material effect on the nano-scale beaming. Several highly conductive metals such as Al, Ag, Ti, and Cr which also have been widely utilized in literatures were compared by tracking focused beam intensity variation along with propagation axis(Z) of a simple 2?m(R=1?m) ring aperture made of each metal. In all the highly conductive metals investigated, less-diffractive beaming was observed and Al gave the highest intensity in the near-field region, however, as the observation point goes away from the metal surface, 2?m ring aperture in Ag slab showed outstanding beaming performance up to Z=5.4?m which is over 10 fold longer than the incident wavelength. Upon setting the metal of interest with Ag, we analyzed the beaming performance with varied parameters of aperture width(W), metal thickness(T) and aperture radius(R). Among various conditions, focused beam with the aperture parameter of W150T100 (i.e., 150nm aperture width and 100nm metal thickness) shows relatively uniform beam diameter of 280nm in the mid-field region of 1~4 ?m. Also a longer radius of the ring aperture delays the less-diffractive uniform nano-scale beaming region slightly to the propagation direction. By focusing incident light to the less-diffractive nano-scale beam, the PL holds a great promise in maskless nanolithography, high-density data storage and optical efficiency improvement of light emitting diode(LED).

8771-46, Session PS

An ultrasensitive metamaterials index sensor by phase interrogation

Hsin Cheng Lee, Ta-Jen Yen, National Tsing Hua Univ. (Taiwan); How-Foo Chen, National Yang-Ming Univ. (Taiwan)

Metamaterials have shown their remarkable applications in biosensing, bioimaging, and nanophotonics. Yet current studies regarding metamaterials as biosensors were restricted in probing the extinction spectra (transmittance or reflectance), and thus lack the complete understanding of metamaterials and limit the performance in biosensing and bioimaging. Here we demonstrated that the optical phase interrogation of metamaterials possesses the superior sensitivity to not only the extinction spectra among the same metallic nanostructures, but also the metamaterials sensors among the current reported studies. Although the sensitivity promotion in phase interrogation is fully understood in surface plasmon polariton (SPP), there is no literature discussed the phase interrogation of metamaterials and their promotion in sensitivity. We believe that phase interrogation is an alternative method in probing metamaterial resonance, and is able to complement the sensitivity insufficiency of metamaterial that interrogated by extinction spectra.

8771-47, Session PS

Electromagnetic parameter retrieval at oblique incidence

Saima I. Khan, Richard De LaRue, Timothy D. Drysdale, Nigel P. Johnson, Univ. of Glasgow (United Kingdom)

Optical metamaterials are able to achieve optical properties that do not exist in nature. Approaches to the homogenization of optical metamaterials are becoming more and more complex in the desire to achieve accurate representation. Here we modify an existing retrieval approach for metamaterials to characterize their properties.

To extract the effective refractive index and other so-called material parameters from reflection and transmission coefficients for double negative metamaterial in the optical regime, the Nicholson-Ross-Weir (NRW) method was modified.

The essence of the NRW method is that in a real composite structure, an equivalent continuous material (with respect to the reflection and transmission of a normally incident plane wave) is substituted. The normalized characteristic impedance and refractive index of this material are found from the Fresnel-Airy formulas for the known reflection and transmission coefficients.

Here we introduce a technique to retrieve effective metamaterial parameters for arbitrary angles of incidence. It employs the complex reflection and transmission coefficients of a finite slab. Expressions for both effective refractive index and impedance are modified for oblique incidence. This method is applied to the fishnet structure.

The modification of the well-known NRW method makes it possible to obtain more informative electromagnetic material parameters for fishnet metamaterial.

8771-48, Session PS

Experimental determination of the effective index of metamaterials

Christelle Tuambilangana, ONERA (France) and Lab. de Photonique et de Nanostructures (France); Petru Ghenuche, Lab. de Photonique et de Nanostructures (France); Julien Jaeck, Riad Haidar, ONERA (France); Stéphane Collin, Lab. de Photonique et de Nanostructures (France)

In this work we propose a novel method for the experimental determination of the complex index of a slab of metamaterial, on a broad wavelength range (1-16 µm) for both polarizations. A diffractive grating is structured out of the metamaterial slab, and the complex coefficients of reflection (r) and transmission (t) are obtained by angle-resolved spectroscopy of the diffracted orders, at any incident angle. The effective permittivity/permeability can be retrieved from r and t. The uniqueness of the solutions is discussed. This method is illustrated in the case of natural dielectric materials, and artificial bi-anisotropic dielectric metamaterials.

The method was first used to measure the complex refractive index of a homogeneous isotropic material (SiNx). We fabricated freestanding structures to avoid multiple reflections in the substrate and simplify the analytical equations for the complex coefficients. The FTIR set-up allows independent angles of excitation and collection, with incidence from 5 to 70°. In a second step, the method is applied to artificial periodic materials. Diffractive gratings are therefore also fabricated out of uniaxial periodic metamaterials. Provided that the period of is small enough compared to the wavelength it could allow to determine their effective refractive index. Oblique incidence measurements can be performed to investigate the spatial dispersion of the artificial material.

[1] C. Billaudeau, S. Collin, C. Sauvan, N. Bardou, F. Pardo, J.-L. Pelouard, Opt. Lett. 33, 165 (2008)

8771-49, Session PS

Yellow phosphor coated with Au/TiO2:Eu thin film for enhanced color rendering index of white LED

Kwang-Cheol Lee, So-Ra Gang, Deok Gi Kim, Sang-Mook Kim, Su Chang Ahn, Korea Photonics Technology Institute (Korea, Republic of)

White light-emitting diode (LED) has dramatically developed and gradually taken over from the conventional light source from several years ago. It is now sufficient for illumination application in performance, while it is still insufficient in color quality. Especially, to trade off the high color rendering properties against the optical loss by multiple phosphor mixing is one of the nuisance for high quality white LED. In this study, we adopted a single sort of phosphor particle with two emission bands in the LED package for high color rendering rather than the combination of two sorts of phosphor particles. For realizing the high color rendering, we combined the blue emission from LED chip with the reddish yellow emission from coated silicate phosphor. Au/TiO2:Eu coating on the surface of phosphor particles was formed by the non-aqueous sol-gel method, which was consisted of the hydrolysis and condensation of titanium isopropoxide, europium nitrate pentahydrate and chloroauric acid. For evaluation, silicate phosphor coated with Au/TiO2:Eu was adopted in the LED package with GaN LED chip. At evaluation of electroluminescence, the silicate phosphor excited by the 465nm blue emission from GaN LED chip had the yellow emission of 570nm peak and TiO2:Eu excited by blue emission emitted the red emission of 617nm peak. Furthermore, phosphor with Au/TiO2:Eu thin film had higher intensity in red emission range than phosphor with TiO2:Eu thin film because Au/TiO2:Eu thin film had high reflectivity in red color band by surface plasmon resonance (SPR). Eventually, improvement of red emission intensity by SPR of Au/TiO2:Eu thin film gave rise to increase the color rendering index in white LED. Besides, silicate phosphor with Au/TiO2:Eu thin film had good moisture stability due to the protecting effect of coating layer. Therefore, it was concluded that Au/TiO2:Eu thin film on the surface of silicate phosphor played the roles of red emission source as well as the protecting layer against moisture and other atmospheric components.

8771-50, Session PS

The formation and structural parameters of new double molybdates RbLn(MoO4)2 (Ln = Pr, Nd, Sm, Eu)

O.D. Chimitova, Baikal Institute of Nature Management (Russian Federation); Victor V. Atuchin, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation); Bair G. Bazarov, Baikal Institute of Nature Management (Russian Federation); Maxim S. Molokeev, Institute of Phsyics (Russian Federation); Zhibzema G. Bazarova, Baikal Institute of Nature Management (Russian Federation)

The laser pumped solid-state lasers based on Ln-doped crystals have found a wide variety of applications in industry. Due to strong distortion of MoO6 octahedrons many molybdates are characterized by noncentrosymmetric crystal structure. Complex molybdates containing rare earth ions are of special interest as effective hosting mediums for lasant ions because the isostructural substitution is possible over wide concentration range. The binary molybdates ALn(MoO4)2 seem to be promising host material for solid-state lasers. Low symmetry positions are observed for Ln3+ ions with benefits for creation of new effective laser mediums. This study is devoted to synthesis of the group of double molybdates RbLn(MoO4)2 (Ln = Pr, Nd, Sm, Eu) and evaluation of morphological, structural and vibrational properties of the compounds.

The formation of RbLn(MoO4)2 compounds has been produced by solid state synthesis. The diffraction data for Rietveld analysis were collected at room temperature (298 K) with a Bruker D8 ADVANCE powder diffractometer in the Bragg-Brentano geometry and linear Vantec detector (CuK? radiation, step size 0.016°, counting time 2s per step). The data were collected over the range 2?: 5-75°. The atomic coordinates in isostructural molybdate TlPr(MoO4)2 were used to refine the structure of the RbLn(MoO4)2 (Ln = Pr, Nd, Sm, Eu) molybdates. The refinement of structure with Pbcn space group was stable and led to minimal

R-factor. Formation of RbSm(MoO4)2 with structural parameters a = 5.14179(1) ?, b = 18.168(6) ?, c = 8.163(2) ?, V = 798.78(4)?106 ?3 was found.

Thus, the crystal family of orthorhombic binary molybdates RbLn3+(MoO4)2 is developed to have wider range of isostructural compounds suitable for lasant-bearing solid solution formation.

8771-51, Session PS

Superconductors in plasmonics and metamaterials: some experimental data

Marcello Gombos, Silvia Romano, Ivo Rendina, Regina Ciancio, Consiglio Nazionale delle Ricerche (Italy); Giovanni Carapella, Univ. degli studi di Salerno (Italy) and Consiglio Nazionale delle Ricerche (Italy); Vito Mocella, Consiglio Nazionale delle Ricerche (Italy)

High frequencies applications of metamaterials and plasmonic structures are strongly limited by dissipative losses in structures, due to poor conductivity of most used metals in this frequency range.

The use of high temperature superconductors (HTSC) is a possible approach to this problem, being HTSC plasmonic materials at nonzero temperature. Negative dielectic constant and variety of charge carriers (electrons or holes) are further very attractive features for plasmonic applications. Characterization of the high frequency response of these materials is then necessary in order to correctly understand the optical parameters of HTSC.

We report on FTIR and ellipsometry measurements on NdBa2Cu3O7-d (Nd123) and the ruthenocuprate superconductor GdSr2RuCu2O8-d (Gd1212) in optical and near infrared regime.

Among YBCO-like cuprate superconductors, Nd123 presents the highest Tc (96K), and the most interesting magnetic response properties.

Even more interesting, in view of use for metamaterial, is Gd1212, whose main characteristic is the coexistence, in the same cell, of superconductivity and magnetic order below Tc: Ru ions intrinsic magnetic moments order themselves below 135K, whereas superconductivity onset is at about 40K, depending on fabrication details.

We performed measurements on Melt-Textured bulk samples, which present the best superconducting properties. Results confirm the promising feature of the considered materials; further analyses, also on powders and films, are in progress.

1] A.H.Majedi, IEEE T.Appl.Supercond. 19, 907 (2009)

2] A.Tsiatmas et Al., Appl.Phys.Lett. 97, 111106 (2010)

3] P.Tassin et Al., Nature Photon. 6, 259 (2012)

4] M.Gombos et Al., Physica C 408-410, 189 (2004)

8771-52, Session PS

Photonic crystal-based high efficiency ultrathin silicon-based solar cells

Principia Dardano, Vito Mocella, Giuseppe De Martino, Ivo Rendina, Istituto per la Microelettronica e Microsistemi (Italy)

Using a random texturing for light trapping in solar cells, the interference between reflected and diffracted waves by the irregular topography leads to internal reflection and the maximum gain depends on the refractive index as 4n2 (Yablonovitch, 1982). For Silicon based solar cells, the maximum gain is about 50 for very weakly absorbed light. Ordered nanostructures show enhanced nearinfrared absorption, which allows their overall sunlight absorption to exceed the Yablonovitch ray-optics light-trapping absorption limit for an equivalent volume of randomly textured planar Si, over a broad range of incidence angles. In this work we present a comparative study on the absorption coefficient in nanopillars and nanoholes ordered structures. In particular we investigate the energy flux in the plane of the cell around pillars and holes in ordered array in condition of normal incidence. We find that, except for small ranges of frequency where is an inversion of tendency, the whole absorption coefficient in nanopillar array is greater than an equivalent nanohole array. Further, the ultimate efficiency of nanopillar array is 138% greater than the ultimate efficiency of a silicon thin film of equivalent thickness. Also, we shows that the ultimate efficiency can be further improved by means of silicon based photonic crystal with an effective negative refraction index. Indeed, negative refractive photonic crystals show a plasmon-like behavior, that is a light confinement in the upper layer useful for absorption improvement in solar cell. Finally, we present some preliminary experimental results on a silicon based photonic crystal with an effective negative refraction index.

8771-53, Session PS

Nonlinear effects in a plasma metamaterial: Raman scattering

Eduardo P. Alves, Univ. Técnica de Lisboa (Portugal); Ricardo A. Fonseca, Univ. Técnica de Lisboa (Portugal) and Univ. de Lisboa (Portugal); Luis O. Silva, Univ. Técnica de Lisboa (Portugal)

Metamaterial research has mainly focused on the use of solid state materials to produce engineered electromagnetic (e.m.) effects. Recently, metamaterials using structured plasmas have been demonstrated to exhibit extraordinary e.m. features [1]. These plasma metamaterials are very attractive due to the high tunability of plasmas by external parameter control, allowing for flexible e.m. responses in comparison with solid state metamaterials. Furthermore, nonlinearities in the permittivity are very natural and easily achieved in plasmas, which may provide new and unexplored phenomena when combined with metamaterial structures.

In this work we investigate the Raman instability [2] in a plasma metamaterial configuration: a bulk plasma embedded in a a medium with a strong magnetic response (provided, for instance, by an array of split-ring-ressonaters). The Raman instability is a nonlinear process based on the interaction of an intense e.m. wave with an electrostatic plasma wave and a scattered e.m. wave. These three waves couple in an unstable manner and lead to the energy transfer of the intense light wave to the scattered light wave mediated by the plasma wave.

Here we generalize the Raman instability theory to incorporate the effect of an arbitrary magnetic medium. Our numerical simulations combine the particle-in-cell (PIC) technique [3] to model the plasma response, and the dispersive-FDTD technique to describe a linear Drude-like response for the magnetic medium. The PIC technique is a standard method to model the fully self-consistent dynamics of the plasma from first principles, which is crucial for capturing the plasma nonlinearities required by the Raman instability. The generalized theory is in good agreement with numerical simulations and we demonstrate the operation of this instability in a parameter window which is not accessible in a simple plasma medium.

[1] Sakai & Tachibana, Plasma Sources Science and Technology 21 (2012)

[2] Forslund, Kindel & Lindman, Physics of Fluids 18, 1002 (1975)

[3] Birdsall & Langdon, Plasma Physics via Computer Simulation (1985)

8771-54, Session PS

Recent advances in the plane wave expansion method in modeling 2D photonic crystal structures

Roman Antos, Martin Veis, Charles Univ. in Prague (Czech Republic)

The plane wave expansion (PWE) method is used to simulate modes and their disperion in 2D photonic crystals (PhC) and waveguides based on them. Each PhC is made as a 2D-periodic array (with square or hexagonal periodicity) of rods or holes with an arbitrary cross-section. Each PhC-based waveguide is made as a line defect in a chosen PhC.

For the first numerical enhancement of the PWE method the complex Fourier factorization is applied, which uses a 2D distribution of generally elliptic polarization bases. With respect to general shapes of the rods/holes, the polarization basis distribution is determined by the electrostatic vector method (EVM) with phase factor modification (PFM). The numerical performance of the EVM-PFM is compared with simulations of the EVM without PFM (corresponding to the normal vector method) and with other factorization methods (where polarization basis distributions are chosen intuitively).

For the second numerical enhancement the adaptive spatial resolution (ASR) is applied, which increases the resolution in the vicinity of the permittivity discontinuities. Convergence properties of the PWE method with and without ASR are compared.

For the third numerical enhancement, related to the PhC waveguides and other finite (aperiodic) PhC-based devices, the method of perfectly matched layers (PML) is applied. The numerical performance of the problem modified by PML is demonstrated with increasing the PhC waveguide supercell.

Finally, further examples of PhC structures are shown made of anisotropic materials (such as magneto-photonic crystals where magneto-optical anisotropy of component materials takes place), and suggestion of 3D genralization of the presented methods is presented.

8771-55, Session PS

Slow light in metamaterial Mach-Zehnder interferometers with arbitrary geometries

Yingying Li, Jie Yuan, Meixiong Chen, National Univ. of Defense Technology (China)

Adopting the tools of transformation optics, we investigate an effective method employed to design metamaterial Mach-Zehnder interferometer with arbitrary geometries. Metamaterial at room temperature to realize slow light is analyzed and summarized in this

paper.The material parameters for Mach-Zehnder interferometer with arbitrary geometries are derived based on transformation-optical approach. The designed Mach-Zehnder interferometer, consisting of waveguides, optical bends, and beam splitters, is actively controlled by changing the material parameters of metamaterial. The properties of metamaterial and the principle of slow light technology are described. Set of criteria are then used to compare several kinds of metamaterial with different configuration parameter. Special attention is given to dispersion of group velocity and loss, which are shown to limit the bandwidth and delay capacity of all the slow light schemes. In the slow-light structure of metamaterial Mach-Zehnder interferometer, the differential of the phase difference introduced by optical path difference is proportional to the group index. Thus, utilizing transformation optics, we can easily design slow-light structure with high dispersion (large group index) based on metamaterial to obtain large sensitivity. Finite element analysis and multiphysics simulation are used to quantify the optical properties of the metamaterial Mach-Zehnder interferometer. Simulation results show that enhancements in sensitivities is gained in the metamaterial Mach-Zehnder interferometer. All theoretical and numerical results validate the material parameters for Mach-Zehnder interferometer with arbitrary geometries we developed. The novel Mach-Zehnder interferometer analyzed in this paper demonstrated a great potential to realize the design of ultra-sensitive and compact integrated rotation sensors with metamaterial.

8771-56, Session PS

Analysis and simulations of one-way waveguide EM structures for THz region

Pavel Kwiecien, Czech Technical Univ. in Prague (Czech Republic); Vladimír Kuzmiak, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Ivan Richter, Czech Technical Univ. in Prague (Czech Republic); Jirí Ctyroky, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

We have developed an efficient 2D numerical technique based on magnetooptic (MO) aperiodic rigorous coupled wave analysis (MOaRCWA). In our in-house tool, the artificial periodicity is imposed within a periodic 1D RCWA method, in the form of the complex transformation and / or uniaxial perfectly matched layers. Our approach, in which several key improvements such as proper Fourier factorization and normal vector method, have been implemented, is able to properly cope not only with SPP propagation in nanostructures, but also with a general form of permittivity / permeability anisotropy, and hence also with the Voigt MO effect. This effect can be used to impose nonreciprocity (one-way propagation) in plasmonic nanostructures bringing new interesting phenomena in connection with magnetoplasmons (MSP). We have employed both the analytic method and the MOaRCWA simulations to study MSP performance in plasmonic nanostructures composed of highly-dispersive polaritonic InSb material in the presence of external magnetic field. In particular, we have explored nonreciprocal behavior of the SPP propagating along the InSb/vacuum interface which reflects variety of interesting features associated with both surface and bulk polaritonic modes within the THz frequency range containing several polaritonic gaps with selective unidirectional propagation.

8771-58, Session PS

Copper silicide processed on silicon substrate by direct laser sintering

Chongwen He, Haihong Zhu, Panpan Hu, Jie Yin, Linda Ke, Huazhong Univ. of Science and Technology (China)

In this paper, metal materials sintering on silicon substrate, which has small coefficients of thermal expansion and brittleness, has been realized. The Cu-P power, pre-alloyed Cu-P powder and SiO_2 power are sintered on Si substrates by Direct Laser Sintering with different mixing ratio. The Cu_3Si detected by X-ray diffraction (XRD) and Field Emission Scanning Electron Microscope (FESEM) is obtained by the mixture of Cu-P power (50%wt) and SiO_2 power (50%wt). The results are analyzed by the reaction diffusion theory and liquid phase sintering growth theory. The experiment reveals a new method which is fast, low-cost than traditional sputtering deposition and metallurgy sintering to fabricate Copper Silicide convenient and random control eutectic area.

8771-20, Session 5

Non-symmetrical hyperbolic media and their potential applications in photovoltaics and photonics *(Invited Paper)*

Igor S. Nefedov, Aalto Univ. School of Science and Technology (Finland); Leonid A. Melnikov, Evgeny I. Nefedov, Saratov State Technical Univ. (Russian Federation)

Media, possessing the hyperbolic-type dispersion, attracts growing attention due to their unusual properties. The hyperbolic dispersion is inherent in uniaxial materials in which the axial and tangential components of the permittivity and/or permeability tensors have different signs. Two main properties of hyperbolic media (HM) cause their potential applications in photonics and (thermo)photovoltaics. The first one is a capability to support propagating waves under any large transversal components of the wave vector (of course, in idealized case). The second one is a high density of modes (infinite in idealized cases).

In this work we present the concept of non-symmetrical hyperbolic media (NSHM) and discuss some possible applications of such media in photovoltaics and photonics. Exotic properties of NSHM are based on non-symmetry of waves propagating upward and downward with respect to slab interfaces. The non-symmetry phenomenon takes place in any structures with tilted anisotropy axes, however it becomes extremely strong in HM media where different components of permittivity tensors have different signs and equal absolute values (satisfy the indefinite medium conditions).

For the transverse-polarized waves, propagating in NSHM, either real or imaginary part of the normal component of the wave vector becomes very large that causes strong wave attenuation even under small material losses. In addition, the perfect matching can be achieved if the wave vector of an incident wave is orthogonal to the anisotropy axis.

Three possible applications are discussed in our presentation. The first one is the total absorption in optically ultrathin layers of NSHM in mid-infrared, near-infrared and visible ranges. We considered the following nanomaterials for design of NSHM: heavily doped silicon, silver nanowire composites, arrays of metallic carbon nanotubes and graphene multilayers. As an example, we demonstrate that the total absorption band 12% can be obtained in a silicon nanowire composite with the thickness of lambda/7.

The second application relates to coherent thermal emission sources. We show that the thermal emission with extremely strong directivity and temporal coherence can be produced by a NSHM slab made of silver nanowires. Modified transfer matrix technique, which is applicable to non-symmetric and non-reciprocal media, and the fluctuating-dissipation theorem are used in the theoretical consideration.

The next idea concerns radiation of small dipoles (molecules). We demonstrate that a weak radiation is not only enhanced, as takes place in media with increased density of states (particularly, in hyperbolic media), but it is transformed also into a very directive light beam outside the NSFM slab that allows its sensing at large distances.

The proposed concept opens a window to novel design ideas for photonics and photovoltaics which can be realized using modern nanotechnologies.

8771-21, Session 5

Terahertz metamaterials based on TiO2 microspheres

Christelle Kadlec, Filip Dominec, Hynek Nemec, Petr Kuzel, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Riad Yahiaoui, Patrick Mounaix, U-Chan Chung, Catherine Elissalde, Mario Maglione, Univ. Bordeaux 1 (France); Filip Kadlec,

Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Motivation

Realization of metamaterials operating at terahertz (THz) frequencies has been under study for the last few years. In our work, we focus on all-dielectric metamaterials based on a single layer of titanium dioxide (TiO2) microspheres. Their effective electric and magnetic responses are related to Mie resonances in the individual particles. For particles with a high-enough dielectric permittivity, a negative effective magnetic permeability was predicted theoretically [1].

Powder preparation

Nanoparticles of TiO2 were mixed with ethanol to obtain a liquid suspension, which was dried upon spraying through flame. This resulted in assembling nanoparticles into fragile mostly spherical clusters. These microspheres were then annealed in a tube furnace at 1200°C for 2 hours, in order to solidify them and to minimize their porosity. The microspheres were finally sieved and sorted according to their diameters. We investigated powders with various diameters, among which the one denoted as MS38/40 (38 µm < diameter < 40 µm).

An original experimental method

We placed a thin layer of TiO2 microparticles between two thick blocks of sapphire separated by a 70 µm thick teflon spacer. This fixes the thickness of the film which is then essentially composed of a single layer of the microparticles. The THz pulses passing directly through the structure enabled us to evaluate the complex transmittance of the powder while the delayed ones, coming from internal reflections on the sapphire/powder interfaces, also included information about the reflectance of the powder. Thanks to this original experimental approach [2], we were able to simultaneously measure the complex transmittance and reflectance of the TiO2 thin layer. Its effective complex permittivity and permeability were then retrieved similarly as in Ref. [3].

Simulations

In order to gain understanding of the electromagnetic resonances, we carried out numerical finite-element simulations of a periodic array of microspheres using commercial software Ansoft HFSS. From the comparison with experimental spectra, we obtained the parameters determining the magnetic resonance: the mean size (39 µm) and the permittivity ?T (92) of the microspheres mainly determine the resonant frequency; the filling fraction F (12 %) controls the resonance strength, and the polydispersity P (8 %) of particles broadens the resonance (the numerical values relate to the powder denoted as MS38/40). We found a good agreement between the measured and calculated permeability spectra.

Conclusion

The experimental method we developed has enabled us to retrieve both permittivity and permeability of thin films from THz transmission experiments. We have proved its strength on TiO2 microspheres by extracting their effective magnetic response. Further simulations have shown that negative permeability can be achieved with such microspheres, either by reducing their polydispersity or by increasing the filling fractions of the films. This could be a way to fabricate cheap metamaterials with negative permeability in the THz range.

[1] S. O'Brien and J. B. Pendry, J. Phys.: Condens. Matter. 14, pp. 4035-4044, 2002.

[2] H. Nemec et al., Appl. Phys. Lett. 100, 061117, 2012.

[3] D. R. Smith et al., Phys. Rev. B 65, 195104, 2002.

8771-22, Session 5

Magneto-optical activity from magnetic and electric dipolar modes in magnetoplasmonic nanodisks

Alfonso Cebollada, Gaspar Armelles, Fernando García, Antonio Garcia-Martin, María Ujué González, David Meneses, Consejo Superior de Investigaciones Científicas (Spain); Nuno de Sousa, Univ. Autónoma de Madrid (Spain); Luis S. Froufe-Pérez, Instituto de Ciencia de Materiales de Madrid (Spain)

Metal-dielectric plasmonic nanodisks show a rich optical behaviour with the appearance of two modes of magnetic and electric dipolar character due to the interaction between the disks. These modes couple to the incident light in a different way, giving rise to regions with low and high optical extinction, respectively. Moreover, the insertion of a ferromagnetic component inside the structure introduces magneto-optical activity in the system. As a consequence, metal-dielectric magnetoplasmonic nanodisks exhibit a rich optical and MO spectral phenomenology. It has previously been shown that, in Au/Co/Au nanodisks where a SiO2 layer is inserted, it is possible to obtain nanodisk configurations for which low optical absorption and large MO activity occur at the same spectral range. This is basically achieved by an adequate positioning of the dielectric component within the structure.

In order to get further information on the behaviour of such systems, here we present our study on the influence that the dielectric spacer thickness has on the interaction between the disks, and as a consequence, on the optical and MO properties of such structures.

The structures consist of a pure Au nanodisk separated by a SiO2 spacer from a MO component constituted by a 4nmAu/2nmCo multilayer nanodisk, which exhibits perpendicular magnetic anisotropy, reducing the required magnetic field to achieve saturation in polar configuration. It will be shown that these structures exhibit the expected magnetic and electric dipolar modes, both in the optical and MO spectra. The position of the magnetic-like mode strongly depends on the SiO2 thickness, while that of the electric like one remains basically unaltered. As the SiO2 thickness is increased, the strength of the MO activity of the magnetic-like dipolar mode increases much more strongly than the corresponding extinction peak. On the other hand, the MO activity of the electric-like mode decreases as the SiO2 thickness increases, while the corresponding extinction peak remains nearly unaffected.

From this analysis a further insigth on the influence of dipole coupling into MO activity can be deduced.

8771-23, Session 5

Coupling mechanisms of resonators in the THz regime

Natalia Gneiding, Erlangen Graduate School in Advanced Optical Technologies (Germany); Oleksandr Zhuromskyy, Max Planck Institute for the Science of Light (Germany); Ulf Peschel, Friedrich-Alexander-Univ. of Erlangen-Nürnberg (Germany)

In metamaterials the response on incident electromagnetic radiation is controlled by tuning the geometric parameters of constituent elements, where collective effects between different resonant elements play a crucial role. To enhance the material's reaction on the magnetic field loop-shaped resonators are usually used. We use the electromagnetic solver (CST MWS) to study ensembles of nano-sized split ring resonators (nano-SRR). In order to predict electromagnetic properties of larger ensembles, which cannot be simulated with the standard electromagnetic simulators because of memory and speed limitations of modern computers, an analytical circuit model is developed. In the framework of the circuit model each resonator is represented by an equivalent LCR circuit and the interaction is accounted for by a coupling constant encompassing both the electric and magnetic coupling mechanisms. The huge leap between modeling the complete complex three dimensional metallic structures and the application of a simplified circuit description is bridged by using the filament current approximation. Here, we show how self-impedance and self-capacitance governing the resonant frequency are deduced from simple considerations concerning the electric and magnetic energies in the individual resonator. The coupling coefficients are obtained from the interaction energies between the currents and charge distributions in neighbouring filaments. The model is verified by comparing the model predictions with the results obtained from the electromagnetic solver (CST MWS). As the resonant frequency of a SRR split when another resonator is brought close to it, the interaction strength between the two resonators is proportional to the resonance position shift. We show that the coupling coefficients obtained from the circuit model are in an excellent agreement with the coupling coefficients deduced from the mode splitting calculated with CST MWS for different inter element distances and mutual orientations.

8771-24, Session 5

Surface plasmon photodetectors *(Invited Paper)*

Pierre Berini, Univ. of Ottawa (Canada)

Surface plasmon (SP) photodetectors, or SP-enhanced photodetectors, combine a metallic nanostructure on which SPs may be excited with a semiconductor detector structure such as a Schottky contact or a pn junction. Involvement of SPs in the photodetection process confers useful characteristics to the detector, such as enhanced photoresponse, spectral selectivity or polarisation sensitivity, which can be exploited to advantage in applications. One application of current interest is the detection of sub-bandgap radiation in silicon at optical communications wavelengths (1310 and 1550 nm) for low-cost optical interconnects and sensing applications. Internal photoemission on metal-silicon Schottky contacts is a broadband detection mechanism (optical and electrical) suitable for such applications but it is inherently inefficient. Structuring Schottky contacts such that SPs are excited at the metal-semiconductor interface results in a significant enhancement of the absorptance and responsivity of the detector. Several structures that exploit SPs to enhance photodetection are discussed and reviewed.

8771-25, Session 5

Hyperbolic metamaterials: what high density of photonic states can do? *(Invited Paper)*

Yuri A. Barnakov, Thejaswi U. Tumkur, J. E. Livenere, Carl E. Bonner Jr., Norfolk State Univ. (United States); Evgenii E. Narimanov, Purdue Univ. (United States); Mikhail A. Noginov, Norfolk State Univ. (United States)

Metamaterials with hyperbolic dispersion, in which dielectric permittivity components in orthogonal directions have different signs, can propagate waves with nearly infinite wave-vectors and possess a broadband singularity in the density of photonic states. The latter property allows one to control a variety of quantum and classical phenomena, including but not limited to scattering and spontaneous emission. In the conference presentation, we will discuss our resent progress in fabrication and characterization of hyperbolic metamaterials as well as effect of the density of photonic states on a variety of physical processes including van der Waals interactions and surface wetting.

8771-26, Session 5

Resolution of near-field to near-field imaging with silver nanolayer

Tomasz Stefaniuk, Piotr Wróbel, Jolanta Borysiuk, Tomasz Szoplik, Univ. of Warsaw (Poland)

Interest in plasmonic superresolving lenses dates back to the paper: Nicholas Fang, Hyesog Lee, Cheng Sun, Xiang Zhang, Sub–Diffraction-Limited Optical Imaging with a Silver Superlens, Science 308, 534 (2005). Here near-field – to – near-field imaging properties of Ag nanolayers with different roughness are studied. Double-sided epi-polished sapphire wafers with C-plane (0001) orientation and an average root mean square (RMS) roughness 0.2nm are used as substrates. On sapphire wafer a non-transparent, that is 50-60 nm thick, layer of chromium is deposited using electron beam physical vapour deposition (e-PVD) system. Then focused ion beam (FIB) system is used to etch chromium completely from a set of slots of widths changing from 50 to 200 nm. Deposition of Al2O3 layer thicker than that of chromium fills the slots and covers all the sample. Then the sample is planarized using FIB and 30-40 nm thick silver nanolayer is added onto Al2O3 using e-PVD system. In one case, Ag nanolayer is deposited at room temperature. In the other case, the sample is cooled down to 90 K what reduces migration of Ag atoms on Al2O3 surface and formation of islands. Thicknesses of all layers are monitored using quartz crystal deposition rate controller. The surface quality is measured with atomic force microscope and expressed in terms of RMS roughness as well as ten point height value given as a difference between 5 maximal peaks and 5 minimal hollows. Near-field image is recorded with scanning near-field optical microscope working in the transmission mode. Samples are illuminated using 100W mercury lamp with filtered wavelengths 404nm, 435nm and 550nm. The sandwich with silver nanolayer deposited at 90 K images with resolution better than diffraction limit.

8771-27, Session 5

Spoof plasmons and their potential in photovoltaics

Constantin Simovski, Aalto Univ. School of Electrical Engineering (Finland)

Thin-film solar cells (TFSC) represent the third generation of solar cells, which are dramatically cheaper and not less efficient than other known types of solar cells with noticeably thick photovolatic layer. The main difficulty for a thin-film solar cell is trapping the incident light. The solar light needs to be specailly concentrated inside the subwavelength thin photovolatic layer (PVL), otherwise the light transmitted into through the rain-protecting covering and anti-reflection coating (ARC) strongly penetrates into the substrate in spite of high optical losses in PVL. Textured ARC which are in principle capable to reduce this harmful transmittance transforming the incident light into waveguide modes of the PVL are restricted for TFSC by the so-called Yablonovicth limit. This situation justifies the use of plasmonic arrays prepared on top of the PVL for trapping the light via the concentration of the light energy inside a very thin layer. In the literature, however, there are not convincing demonstrations that plasmonic arrays offer the stronger photovoltaic absorption than ARC. Though the literature on plasmonic light-trapping structures (LTS) is abundant, two inherent drawbacks persist: a narrow frequency band of any plasmon resonance (that drawback keeps for multi-resonant arrays, too) and inevitable dissipative losses of plasmonic nanoparticles at these resonances. Therefore it would be importnt to find a regime where the hot spots inside the PVL are produced beyond plasmon resonances. In this paper, we suggest and study theoretically a novel LTS based on the use of spoof plasmons excited in arrays of nanoantennas at wavelengths quite distant from plasmon resonances. The chessboard-like modes excited in our structures are analogous to the collective oscillations earlier revealed for arrays of parallel metal bars operating in the far-infrared range and termed domino modes. Such modes can be excited at many wavelengths when the electric field is orthogonal to the bar axes. The main feature of domino modes is the advantageous distribution of the local electric field concentrated in the gaps between the bars. The internal field in metal is small, and consequently these modes demonstrate low losses. In several earlier studies, domino modes were excited only by an incoming beam with the grazing incidence on the array plane. However, our simulations reveal that these modes are also excited for any angle of incidence (e.g. zero angle). We have shown that these modes can be excited also in the visible range. The analysis of their properties shows high potential of these modes for the design of LTS. We achieved in simulations the substantial enhancement of the photo-absorption in very thin (100-150 nm) semiconductor layers. The useful absorption significantly exceeds that granted by a simple ARC (a flat blooming layer with optimized thickness and refraction index).

8771-28, Session 5

Plasmon spectroscopy and imaging of individual metal nanoparticles

Viktor Myroshnychenko, F. Javier García de Abajo, Consejo Superior de Investigaciones Científicas (Spain)

Knowledge and experimental access to the electromagnetic field distributions associated to localized plasmon excitations in metal nanoparticles, with high degree of energy and spatial resolution, are of critical importance in the development of applications. In this work, we review the use of optical spectroscopy, electron-induced radiation emission (cathodoluminescence), and electron energy-loss spectroscopy to study localized surface plasmon excitations in sub-wavelength noble-metal nanoparticles prepared via lithography

or colloidal chemistry. These techniques provide information about plasmon excitations by recording different physical processes, specifically, light scattering exerted by the particles on externally incoming light, radiation emission produced by interaction with an electron beam, and energy loss suffered by those electrons. We provide a theoretical description of a study of the spectral features and spatially resolved maps of nanoparticle plasmon modes at the single-particle level by using these techniques. We discuss the similarities and differences between these techniques as well as a comparative analysis of the information that they provide. Numerical modeling is carried out for each set of experimental measurements in order to interpret the results and understand the nature of the excited plasmons. Spectral features and spatially-resolved maps of SP modes collected for individual nanoparticles of different morphologies are shown to be in good agreement with theoretical calculations obtained using the boundary element method based upon rigorous solution of Maxwell's equations. Our comparative assessment of the experimental techniques used in this work demonstrates an extremely high capability of electron energy-loss spectroscopy and cathodoluminescence in resolving and imaging surface plasmons in small subwavelength metal nanoparticles with unrivalled spatial and energy resolution.

8771-29, Session 7

Taming light-matter interaction on the nanometer scale *(Invited Paper)*

Romain Quidant, ICFO - Institut de Ciències Fotòniques (Spain)

Extensive research in plasmonics over the last decade has demonstrated the ability of noble metal nanostructures to concentrate optical fields down to the nanometer scale. Such control of light, well beyond the limit of diffraction, potentially opens new opportunities for enhanced interaction with tiny amounts of matter down to the single molecule/atom level. In practice though, fully exploiting the capability of plasmonics requires nanoscale positioning of the molecule/atoms within the hot spot, where the light is concentrated.

In this talk, we first present different experimental strategies to accurately control the interaction of top-down metallic nanostructures with few to single molecules or artificial atoms. We then discuss some applications to different areas including nanochemistry and quantum optics.

8771-31, Session 7

Reduction of surface roughness of Ag nanolayers on cooled and wetted substrates

Piotr Wróbel, Tomasz Stefaniuk, Tomasz Szoplik, Univ. of Warsaw (Poland)

In this technical note we present our technology in fabrication silver nanolayers with ultrasmooth surfaces. We are motivated by our interest in applications of single Ag nanolayers and silver-dielectric multilayers where long range propagation of plasmons is possible due to low losses. The vacuum chamber is pumped out down to a pressure of 10-8 Torr. Ag pellets are bombarded with electrons and silver vapours deposit on polished fused silica and sapphire substrates. The liner-substrate distance is about 45 cm. In order to reduce roughness of Ag films we use nanometer thick seed growth layers of Ge. To avoid migration of deposited atoms on substrate surface the substrates are cooled with liquid nitrogen. We deposit layers on substrates cooled and heated to temperatures from the range 90 - 500 K. Temperature sensors have accuracy better than one centigrade, however during deposition temperature increases with evaporation time. Therefore substrate temperature is given with +/- 5 centigrades accuracy. The other parameter of the physical vapour deposition (PVD) process is a deposition rate which varies within the range 2 to 10 angstroms/s and is measured with quartz crystal rate controller. The surface quality is measured with atomic force microscope and expressed in terms of an average root mean square (RMS) roughness and ten point height value given as a difference between 5 maximal peaks and 5 minimal hollows. For layers deposited on wetted substrates at the lowest temperatures RMS values smaller than 4 angstroms on surfaces of ten squared micrometers are achieved. In the developed PVD experimental system there is a possibility of sequential cooling and heating of substrates in the same vacuum process.

8771-32, Session 7

Highly organized plasmonic nanoparticles: macroscopic optical tuning a step towards metamaterials

Nicolas Pazos Perez, Univ. Bayreuth (Germany); Ramon A. Alvarez-Puebla, Univ. Rovira i Virgili (Spain); Andreas Fery, Univ. Bayreuth (Germany)

Plasmonic nanoparticles are excellent candidates for their potential use in microelectronic, optical, biomedical applications or to develop new metamaterial properties. Their individual electromagnetic behaviour is highly dependent on their specific size, shape, and surrounding environment of the particles. There are different methods which allow us to fine tune the control over these parameters and thus, the materials properties. However, the lack of capability to form reproducible organized structures at large scales is still a very important challenge to solve in order to control the plasmonic inter-coupling between particles and their collective behaviour. This is a crucial point for their incorporation into new technological devices. Therefore, it is clear that their controlled organization in 2D and 3D structures is of key importance. In this work we report novel methods to produce large scale organized structures of plasmonic nanoparticles. These organizations can be done either at the macroscale or at the nanoscale using completely lithography-free approaches.

Macroscale organizations as monolayers, supercrystals, and periodic linear arrays with tuneable width and spacing between lines were created via spin coating, confinement controlled drying, and the combination of both techniques.

Assemblies of particles at the nanoscale regime were performed through a controllable cluster formation with variable coordination numbers (dimmers, trimmers, tetrahedrons...).

The plasmonic behaviour of these organizations was theoretically and experimentally investigated. Moreover, these structures, were effectively use for sensing using Surface-enhanced Raman scattering (SERS) spectroscopy.

8771-33, Session 7

Block-copolymer-based plasmonic metamaterials

Antonio Capretti, Finizia Auriemma, Claudio De Rosa, Rocco Di Girolamo, Carlo Forestiere, Giovanni Miano, Giovanni P. Pepe, Univ. degli Studi di Napoli Federico II (Italy)

Block-copolymer (BCP) self-assembling provides a unique tool for realizing large-area ordered metamaterials, with desired optical properties. The benefits of using BCPs as templates for metamaterials come from two main aspects: first, BCPs show a rich range of available nano-morphologies, whose domains can be conveniently tuned in size, shape and periodicity, by changing molecular parameters; second, the chemical properties of the block polymers can lead to the selective inclusion of functionalized nanoparticles (NPs) of different materials in specific nanodomains, generating periodic arrays of NPs according to the geometry of the BCP acting as template. This approach allows finely modulating the optical properties of NPs and can be used as an intriguing and versatile tool to build useful devices for Optics & Photonics applications, with significant benefits for both fundamental and applied investigations.

In this work, we investigate nanostructured thin films of polystyrene-block-poly(methyl methacrylate) BCP (PS-PMMA), characterized by an hexagonal array of PS cylinders in the PMMA matrix. The PS cylindrical domain are selectively filled by functionalized metallic (Au, Ag) NPs. The optical properties of such nano-structures are strongly affected by localized surface plasmons (LSPs) in the NPs, arising from the collective resonances of conduction electrons in the metal at a characteristic spectral range, usually in the visible range. LSPs induce high field enhancement (FE), with respect to an incident light, in proximity of the NP surface, and in particular in the gap between two close NPs (hot-spot). Moreover, LSPs increase the intensity of absorption and scattering of light by the NPs in their range of resonance.

The optical properties of the PS-PMMA films, with selectively included NPs, are numerically investigated by means of electromagnetic models of increasing complexity. The overall periodic morphology is studied under the approximation that the PS cylindrical domains were completely filled by one monolithic metal particle. In particular, the hot spot of the nano-structure are considered and the FE evaluated. Moreover, the calculations are extended to establish the optical properties of a single PS domain as a function of the filling fraction of Au NPs, up to the small-size NPs limit, where potential quantum effects are expected. The results of these calculations are compared with experimental data obtained by measurements of intensity of absorption and scattering of light from NPs embedded in the nanostructured PS-PMMA thin films support as a function of morphological parameters and metallic Au NPs filling fractions. Accordingly, potential applications of BCP-based metamaterials and their future developments in the field of optoelectronics are also discussed.

8771-34, Session 8

Beam reflections from one-dimensionally modulated photonic structures *(Invited Paper)*

Kestutis Staliunas, Yu-Chieh Cheng, Univ. Politècnica de Catalunya (Spain); Martynas Peckus, Vilnius Univ. (Lithuania); Simonas Kicas, Institute of Physics (Lithuania); Jose Trull, Crina M. Cojocaru, Ramon A. Vilaseca, Univ. Politècnica de Catalunya (Spain); Ramutis Drazdys, Institute of Physics (Lithuania)

We explore reflections of narrow beams from one-dimensionally modulated photonic structures, where the modulation period varies across the structure (the so called chirped dielectric mirrors).

It is known, that the plane waves reflected in a normal direction from the chirped mirrors, can show modified temporal dispersion [1]. Different frequency components reflect from the different depth of the structure, as shown in Fig.1.a. As a consequence the pulses reflected from such mirrors can obtain a chirp, or contrarily, a pulse chirp of opposite sign can be compensated in reflection. We argue, that the character of reflection of narrow beams from such a chirped structure can be also very peculiar. The plane wave components (angular components) of the beam also reflect from the different depth of the structure (see illustration in Fig.1.b), which can result in modification of the spatial dispersion. The beam, in this way could obtain important spatial transformations during reflections. In particular a focalisation of the beam could be possible, as shown in Fig.1.c.

Our calculations using multiple matrix transfer method, also the full FDTD calculations, show the expected beam shaping and, in particular, evidence beam focalisation effect in reflections. Experimental measurements of beam reflections from chirped mirrors the beam shaping and focalisation, and will be reported in the presentation.

REFERENCES

[1] R. Szipöcs et al., “Chirped multilayer coatings for broad-band dispersion control in femtosecond lasers”, Opt. Lett. 19 (3), 201 (1994);

8771-35, Session 8

Study of the anomalous refraction produced by self assembled gold nanowires

Concita Sibilia, Alessandro Belardini, Univ. degli Studi di Roma La Sapienza (Italy)

F. Capasso and coworkers [1] shown that resonant metallic nanostructures at the interface between two dielectrics can bent a ray of light by following a generalized Snell’s law [1].

The generalized Snell’s law can also be used as a powerful tool in the subwavelength characterization of nanopatterned surfaces.

Here we report the measurements at lambda=633nm of the anomalous refraction produced by a metasurface made up of self assembled bent gold nanowires arrays, 1-2 micron length, with a section of 40nm and radius of curvature of 400nm. The measurements clearly show the dependence on the morphology of the nanowires.

The realized set-up is constituted by a He-Ne leaser entering in the sample at different incidence angle, meanwhile the output is recorded by a quadrant detector that gives, as a function of the incidence angle, the displacement of the beam and its total power.

The polarization of the light was set in order to excite the plasmonic resonance, i.e. with the polarization of the light perpendicular to the wires direction [2].

The results demonstrate that the deviation measurement set-up can be a sensitive method for sub-wavelength morphological analysis of nano-structured samples: the direction of the radius of curvature of the wires influences the displacement of the light on the detector meanwhile the total transmitted intensity of the light brings information on the average tilt of the wires. These behaviour can be compared with more complicated nonlinear optics techniques that gives similar information [3,4]. We think that the simplicity of the experimental set-up and his high sensitivity can be also used in order to investigate other types of nanostructured materials.

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

2. A. Belardini, F. Pannone, G. Leahu, M. C. Larciprete, M. Centini, C. Sibilia, C. Martella, M. Giordano, D. Chiappe, and F. Buatier de Mongeot, Appl. Phys. Lett. 100, 251109 (2012).

3. A. Belardini, M. C. Larciprete, M. Centini, E. Fazio, C. Sibilia, M. Bertolotti, A. Toma, D. Chiappe, F. Buatier de Mongeot, Opt. Express 17, 3603-3609 (2009).

4. A. Belardini, M. C. Larciprete, M. Centini, E. Fazio, C. Sibilia, D. Chiappe, C. Martella, A. Toma, M. Giordano, and F. Buatier de Mongeot, Phys. Rev. Lett. 107, 257401 (2011).

8771-37, Session 8

Metamaterial fishnet structure formed from nanoimprint lithography with resonances at near infra-red and visible wavelengths

Graham J. Sharp, Murat Yuce, Univ. of Glasgow (United Kingdom); Xiaolon Hu, City Univ. of Hong Kong (Hong Kong, China) and Univ. of Glasgow (United Kingdom); Mantana Sinworapun, Ali Z. Khokhar, Nigel P. Johnson, Univ. of Glasgow (United Kingdom)

We report on the fabrication and characterisation of fishnet structures of various dimensions on a polymer layer with metal-dielectric-metal rectangular pillars suppressed beneath. The metamaterial structures are fabricated using nanoimprint lithography, allowing large areas to be patterned quickly and good reproducibility through multiple use of the nanoimprint stamp. Multiple layers of silver (Ag) and magnesium fluoride (MgF_2) were deposited on a thick polymer layer, in this instance PMMA, before being directly imprinted by a stamp. When the metal-dielectric layered pillars are imprinted to a sufficient depth in the PMMA below the fishnet, distinct resonance peaks can be measured at both visible and near-infrared frequencies. The precise wavelength of the resonant peak at near-infrared and its Q-factor can be changed by altering the physical dimensions and number of metal and dielectric layers of the fishnet respectively. The response viewed at visible frequencies is due to the pillars that sit in the PMMA, below the fishnet.

Silver and magnesium fluoride layers that comprise the suppressed pillars are crushed during the imprinting process and their total thickness reduced. However despite imprinting directly into multiple metal and dielectric layers, high quality structures are observed with a minimum feature size as low as 200 nm. Resonance peaks are measured experimentally in reflectance using an FTIR spectrometer with a calcium fluoride (CaF_2) beam-splitter and a visible wavelength range spectrometer with a silicon (Si) detector. Simulated modelling of the structures, comprising of both the fishnets and pillars in their 3D arrangement, is also included and the results compared with the experimental measurements.

8771-38, Session 8

A simple model of a two-dimensional quantum metamaterial

Mark J. Everitt, John H. Samson, S. E. Salelev, Loughborough Univ. (United Kingdom); T. P. Spiller, Univ. of Leeds (United Kingdom); Richard D. Wilson, Alexandre M. Zagoskin, Loughborough Univ. (United Kingdom)

We consider a two-dimensional metamaterial comprising an array of qubits (two level quantum objects). Here we show that a two-dimensional quantum metamaterial may be controlled, e.g., via the application of a magnetic flux, so as to provide controllable refraction of an input signal. We investigate the role of measurement on the operation of the metamaterial. We note that the application of an external control parameter can be used to change the behaviour of the material. We note that quantum metamaterials as proposed here may be fabricated from a variety of current candidate technologies from superconducting qubits to quantum dots. Thus the ideas proposed in this work would be readily testable in existing state of the art laboratories.

8772-1, Session 1

Nonlinear probes of chirality *(Invited Paper)*

Martti Kauranen, Tampere Univ. of Technology (Finland)

No Abstract Available

8772-2, Session 1

Measurement of the circular dichroism in the second harmonic optical signal produced by Au covered self ordered dielectric nanospheres

Concita Sibilia, Alessandro Belardini, Univ. degli Studi di Roma La Sapienza (Italy)

Here we present the measurements of the second harmonic generation (SHG) signal raised by self ordered dielectric nanospheres partially covered by thin (10nm) Au layer. The measurement were performed by studying the SHG efficiency in different polarization states of the light. In particular measurement performed with circular polarized light show the presence of chiral response of the nanospheres that is induced by the particular geometry of the metasurface. In the field of nanophotonics the artificial circular dichroism [1] is investigated for developing novel compact devices for optical signal manipulation or molecular sensing; here we investigate samples produced by a self assembled procedure that guarantees large are fabrication with low time consuming procedure. We show that the artificial chirality in this material [2,3] arises from the curvature of the gold layer covering the nanospheres, by comparing the signal of samples with different spheres radii, and also depends on the geometrical shape of the coupling of the metal layers between adjacent spheres [4]. We also investigated the effect of the plasmonic and optical resonances on the magnitude of the SHG signal. In the samples that we studied in fact there is a cooperation between the field enhancement at the first harmonic frequency due to localized plamsonic resonance of gold and the coupling of the field at second harmonic frequency with the collective resonant mode of the dielectric spheres.

[1] A. S. Schwanecke, A. Krasavin, D.M. Bagnall, A. Potts, A.V. Zayats, and N. I. Zheludev, Phys. Rev. Lett. 91, 247404 (2003).

[2] T. Verbiest, M. Kauranen, Y. Van Rompaey, A. Persoons, Phys. Rev. Lett. 77, 1456 (1996).

[3] E. Plum, X.-X. Liu, V. A. Fedotov, Y. Chen, D. P. Tsai, and N. I. Zheludev, Phys. Rev. Lett. 102, 113902 (2009).

[4] A. Belardini, M. C. Larciprete, M. Centini, E. Fazio, C. Sibilia, D. Chiappe, C. Martella, A. Toma, F. Buatier de Mongeot, Phys. Rev. Lett. 107, 257401 (2011).

8772-3, Session 1

Nonlocal nonlinear-magnetooptical response of a plasmonic crystal

Ilya Razdolski, Diana G. Gheorghe, Radboud Univ. Nijmegen (Netherlands); Evangelos Papaioannou, Uppsala Univ. (Sweden); Andrei Kirilyuk, Alexey V. Kimel, Theo Rasing, Radboud Univ. Nijmegen (Netherlands)

Efficiency of coupling light with matter is one of the most topical challenges of modern photonics [1]. An elegant solution for this is the surface plasmon resonance excited in metamaterials, or regular arrays of nano-scaled objects. They allow direct optical excitation of a plasmon on an air-metal interface [2], which is not possible in the case of a plain metallic surface. Here we demonstrate how the excitation of a surface plasmon can substantially modify the nonlinear-optical response of a 2D magnetoplasmonic crystal and even introduce a new source of a second harmonic generation (SHG) with an unique symmetry.

The sample we studied was a 60-nm thick Co film covered with a 2-nm Au layer and perforated by a hexagonal array of antidots, 250 nm in diameter and with a lattice period of 470 nm. Resonances in linear reflectivity and magneto-optical Kerr rotation displaying the proper symmetry have been recently reported on a similar structure [3]. The nonlinear-optical experiments were carried out in the transversal Kerr geometry, where the outcoming p-polarised SHG radiation experiences an intensity change upon switching the external magnetic field polarity.

Anisotropic SHG measurements in the vicinity of the plasmon resonance revealed an enhancement of nearly one order of magnitude of the SHG signal at resonance, as compared to the off-resonant conditions or reference plain film. In addition, the symmetry of the SHG enhancement reflects the sixfold symmetry of the antidots array and proves that the antidots structure is responsible for the SHG efficiency increase.

For the reference film, transversal Kerr effect conventionally described by a magnetic contrast ? = (I?-I?)/(I?+I?) showed no noticeable spectral or angular dependence. In striking difference, for the perforated film, the magnetic contrast experienced dramatic changes with angle of incidence, including the sign reversal. Moreover, the effect proved its plasmonic nature by shifting with the excitation wavelength according to the well-known plasmon excitation relations [2]. Phase-sensitive measurements allowed to disentangle SH contributions with different symmetry with respect to the sample magnetization. The SH response odd-in magnetization was found to be strongly modified in the vicinity of the plasmon resonance, both in its magnitude and phase.

A symmetry analysis of the nonlinear polarization showed that a new nonlocal SH source is activated in the vicinity of the resonance. Its quadrupole non-locality stems from the plasmon wave-modulated electromagnetic field distribution. Due to the symmetry reasons it is only the SH signal odd in magnetization which exhibits such a resonant behaviour, while the even SH contribution retains its predominantly dipole nature. Thus, an excitation of a surface plasmon was demonstrated to modify the symmetry of a nonlinear system and even activate new sources of the nonlinear-optical response.

[1] J.A. Schuller et al., Nat. Mater., 9, 193 (2010).

[2] H. Raether, Surface Plasmons on Smooth and Rough Surfaces and on Gratings (Springer-Verlag, Berlin, 1988).

[3] E.Th. Papaioannou et. al., Opt. Express, 19, 24 (2011).

8772-5, Session 1

Time domain analysis of nonlinear photonic crystal waveguide

Yasin Farzami, Mahdi Davoodi, Malek Ashtar Univ. of Technology (Iran, Islamic Republic of)

In this research, the nonlinear photonic crystal waveguide is analyzed using two dimensional finite-difference time-domain method. We assume that waveguide is formed by a single line-defect in PC triangular lattice, where the line-defect region of waveguide is made of ?(3) nonlinear material. The intrinsic nature of the constitutive relation for this type of nonlinear material leads to couple between orthogonal polarizations. Our FDTD method is based on a modification of the original Yee's FDTD algorithm. Simple but robust technique is used to solve nonlinear constitutive relations and include dispersion in FDTD formulation. In this algorithm, finite time response is considered to nonlinear effects and polarization in FDTD formulation is calculated by previous amounts of polarization and electric fields. The source is Huygens source with a Gaussian frequency spectrum and having both TE and TM components with equal amplitudes. The relatively large nonlinear values are used to observe the effects of the nonlinear material without simulating a very large computational domain. We use triangular lattice PC geometry because of its large bandgap for TM polarization. Simulation results show that some power transfer from TM to TE polarization and the transmission exceeds 1 for some normalized frequencies. However, the frequencies where the gain is observed are outside of bandgap, and thus only weakly guided with likely large propagation loss into PC cladding. The largest gain, at the

normalized center frequency of the source, is 2.98dB with compared to the linear PCWG transmission. The lack of significant change in the transmission for the TM cases and for the smaller value of nonlinearity for TE indicates that the frequency mixing effects have been largely suppressed. The transmission spectrum on a log scale is shown that significant power is being converted to the third harmonic rather than TM to TE power conversion. This is due to the fact that both TM and TE signals experience third harmonic generation and thus depletion at the pump wavelength, whereas the TM-to-TE conversion only produces gain for TE while further depleting the TM. This results from SPM arising from the Kerr-type nonlinearity, due to the dispersion of PC waveguide. In our simulation, PML boundary condition is specified at four computational boundaries. It is shown that Yee's FDTD algorithm is stable under Courant's stability condition for nonlinear effects.

8772-6, Session 2

Chalcogenide planar waveguide platform for supercontinuum generation in mid-infrared

Duk-Yong Choi, The Australian National Univ. (Australia); Pan Ma, Australian National Univ. (Australia); Xin Gai, Zhiyong Yang, Steve J. Madden, Barry Luther-Davies, The Australian National Univ. (Australia)

Recently, there has been growing interest in extending the spectral coverage of supercontinuum generation (SCG) to the molecular fingerprint region (2-25μm) in the mid-infrared (MIR) where bright, broadband sources are lacking. Extending the output of SC waveguide sources into the MIR is, however, far from trivial. It requires new materials transparent over the 2-20μm range that also have high optical nonlinearity and a good resistance to optical damage. In this context chalcogenide glasses (ChG) are an ideal choice for MIR SCG. The main challenge is, however, to develop optimized glasses free from impurities and fabricate them into dispersion-engineered waveguides. In this perspective we already demonstrated that our ChG optical devices can efficiently generate near-IR SC [1] establishing the feasibility of using planar optical waveguides rather than fibers. Waveguides have the advantage of requiring low pulse powers because of their high nonlinearity and can be easier to fabricate than fibers. In 2012 [2] we also presented the first report of SCG in an As2S3 planar waveguide in which the spectral width achieved was limited to the range from 2.9μm to 4.2μm. This was the first report of SCG in the MIR from a planar waveguide.

In this paper we present a ChG waveguide structure having low propagation loss in 3/5μm spectral range, which is an imperative to extending the output of SC into longer wavelengths. In previous report [2] we used thermal oxide (SiO2) as an underclad so that it starts to be opaque from 4μm. We replaced it with MgF2 substrate that has a very wide transmission window from ultraviolet up to 8μm. For a core region, Ge11.5As24Se64.5 film with 2.5μm thickness was thermally evaporated on to magnesium fluoride, then patterned into rib-structure employing photolithography and plasma etching. The waveguide width and rib height were 4, and 1 micron, respectively, and we verified that the structure shows quasi-single mode behavior. This specific composition of ChG has three times higher nonlinearity over As2S3 [3]; hence this enables SCG possible at lower peak power and/or shorter device. We tested an air-clad Ge-As-Se guide on MgF2 using cut-back technique within 3/5μm span. The lowest loss, 0.5dB/cm, was measured at 5μm in TE mode; however, a broad peak centred at 3.2μm was observed to reach 3.5dB/cm. We speculate that this originates from the absorption of hydrocarbon bonds on unprotected ChG waveguide because it is known CH bonds from inadventitious carbon contaminate any surface exposed to air. In order to prevent the contamination a proper upperclad material should be coated under vacuum, following ChG etching. We exploited the plasma polymerization of CHF3 gas, and deposited one micron thick teflon-like layer which is transparent up to 8μm wavelength. As expected, the absorption peak disappeared and the loss was in a range of 0.5 to 1.5 dB/cm in 3/5μm window. This low-loss feature supports that our ChG waveguide platform is promising for SCG in MIR; furthermore, as evidenced from CH detecting capability, we can apply it for molecular bonds sensing device as well.

[1] M.R.E. Lamont, et al., Opt. Express 16, 14938 (2008).

[2] D.A.P. Bulla, et al., Appl. Phys. 96, 615 (2009).

[3] Xin Gai, et al., Opt. Lett. 37, 3870 (2012).

8772-7, Session 2

Nonlinear effects and models of physical processes in composite nanoparticles of copper halides, silver and silver halides embedded in the single volume under the laser pulse radiation

Alexander A. Kim, Nikolay V. Nikonorov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation); Aleksandr I. Sidorov, Saint Petersburg Electrotechnical Univ. "LETI" (Russian Federation); Viktor A. Tekhomsky, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

Glass-ceramics based on the glass matrix with composite nanoparticles of copper halides, silver and silver halides under the influence of laser radiation demonstrated the effect of optical confinement in a broad spectral range. The relaxation time of photochromic process in case of copper halides is usually an order of magnitude compared with the excitation pulse and takes moreover 50 ms, that is not suitable for modern optical devices. The saturable absorption due to silver plasmonic effects is limited by non-effective attenuation coefficient.

Main interest is focused on the experiments that provide the photochromic properties of copper halides glasses and plasmonic effects of silver nanoparticles that located in the same volume. The previous experimental results showed the effective confinement of copper chloride nanoparticles embedded in glass matrix, and the saturable absorption of silver nanoparticles embedded in glass matrix.

We have studied experimentally the nonlinear optical effects in glass-ceramics with copper chloride, and mixed copper chloride – copper bromide nanoparticles in a single volume. These materials showed a wide dynamic range of the effect of the nonlinear optical limitation from 10-10 to 10-4 J/cm2 in silicate glass matrix, and from 10-6 to 10-3 J/cm2 in potassium-aluminum-borate glass matrix. This work paid special attention to the understanding of physical process modeling. The main processes include change the effective index of refraction of the laser beam and the formation of negative dynamic lens due to:

- photogeneration of free carrier – electrons;
- thermal expansions on the axis of light distribution;
- free-carrier absorption;
- photogeneration of non-stable optical color centers;
- Two-photon generation at high energies 10-4-10-2 J/cm2

Photogeneration of free carrier normally appeared from the interband impurity energy level into the bandgap of copper halides nanoparticles. The presence of impurities in wide-gap semiconductors generates additional levels and accordingly creates a saturating nonlinear-optical limitation. Saturation of interband absorption, photogeneration of color centers leads to a change in the refractive index and other effects. The formation of the negative dynamic thermal lens due to the high coefficient of thermal expansion (CTE) CuCl nanocrystals with respect to the CTE of the glass matrix. The formation of such unstable centers, whose life can vary widely from 10-12 to10-5 s, depending on the size effect can occur in a wide range of excitation energy from 10-10 to 10-3 J/cm2.

We expect the more effective attenuation coefficient due to combine system of composite nanoparticles of silver, silver halides and copper halides in the same volume embedded in glass matrix. The key point is make stronger attenuation coefficient and decrease the relaxation time of a system after laser pulse.

8772-8, Session 2

Angular-tuning of optical parametric generation efficiency in 2D periodically poled lithium tantalate

Mohamed Lazoul, Univ. Paris 13 (France) and Ecole Militaire Polytechnique (Algeria); Simohamed M. Lotfy, Ecole Militaire Polytechnique (Algeria); Lung Han Peng, National Taiwan Univ. (Taiwan); Alexis P. Fischer, Azzedine Boudrioua, Univ. Paris 13 (France)

In this work we report optical parametric generation in two dimensional, second order periodically poled lithium tantalate crystals. We are particularly interested by angular tuning of the conversion efficiency.

For this purpose a two dimensional periodically poled lithium tantalate (2D-PPLT) crystal was designed and fabricated by the electrical poling technique. The poled regions are circular and periodically organized according to a square lattice with a grating period of 8.52 ?m. The sample is mounted inside a temperature controlled oven and placed on a rotation stage allowing variation of the pump beam incidence angle. The pumping source consists on a q-switched Nd:Yag laser at 532 nm with a pulse duration of 5 ns. In order to use the crystal largest nonlinear coefficient d33, the pump polarization is aligned with the PPLT Z-axis.

We are interested in investigating the variation of the generated energy and therefore the efficiency of the nonlinear process as a function of the incidence angle of the pump beam.

Therefore, we slowly changed the incidence angle by rotating the crystal. We observe that when going away from the pump collinear direction to a non-collinear direction, the signal wave intensity gradually decreases and reaches a minimum value. After that it begins to rise progressively to almost the same level as in the collinear direction.

In order to explain this oscillatory behavior of the parametric conversion efficiency, we considered the analogy between quasi-phase matching in nonlinear photonic crystals and X-ray diffraction in solids. A double circle construction, different from the conventional Ewald sphere, is adopted to explain the quasi phase matching process. This latter, theoretically, predicted that angular tuning may be a powerful route for enhancing the conversion efficiency in 2D nonlinear photonic crystals. We experimentally demonstrate that the generated intensity can be driven by the incidence angle of the pump beam.

Finally, this study emphasizes an easy but efficient way to control the generated waves' intensities in the case of parametric nonlinear interactions in 2D nonlinear photonic crystals.

8772-9, Session 2

Self-diffraction of laser beams in the case of resonant excitation of excitons in colloidal CdSe/ZnS quantum dots

Alexander Smirnov, Vladimir S. Dneprovskii, Maria Kozlova, Lomonosov Moscow State Univ. (Russian Federation)

Self-diffraction of two types has been discovered in the case of one- and two-photon resonant excitation of the allowed basic exciton transitions of colloidal in CdSe/ZnS quantum dots by two intersecting high-power second harmonic beams of mode-locked laser with picosecond pulse duration. The physical processes responsible for the nonlinear optical properties of CdSe/ZnS quantum dots and for the arising self-action effects are discussed. Two types of self-action process may arise in resonantly absorbing medium. 1. In the case of efficient nonlinear absorption (saturation of optical transition) the high-power laser beam may format the transparency channel, the induced diaphragm and thus the beam's self-diffraction may arise. 2. Due to self-action of two intersecting laser beams in nonlinear medium periodic spatial modification of electric field (intensity) dielectric susceptibility may arise as a sequent of cubic nonlinearity. The interaction of two coherent light waves in an absorbing medium leads to the periodic modulation of the optical properties of the material with further diffraction of the primary waves on the formed grating. Transient grating technique allowed to calculate the duration of exciting Gaussian laser pulses by measuring only energies and delay between two identical pulses that induce the grating in absorbing medium.

The diffraction rings typical for Fresnel diffraction arise for penetrated through the cell with QDs beams that hold the direction of incident beams' spreading. Their identical cross-section intensity distribution with maximum or minimum in the centre and different number of rings depends on the intensity of the incident beam. The revealed radiation intensity distribution of beams can be explained by the creation of transparency channel in the sell due to propagation of high-power beams resonantly exciting the basic electron-hole transition in CdSe/ZnS QDs. With penetration into colloidal solution of QDs the light beam with Gaussian cross section distribution of the intensity loses its low-intensity peripheral parts due to stronger absorption than at the center on its axis (beam's "stripping"). Thus strip effect results in a profile change of the beam, whose edges transform from smooth into sharp ones, and in creation of induced "rigid" diaphragm. The formation of rings with a maximum or a minimum in the centre may be attributed to Fresnel diffraction from a circular induced aperture with diameter depending on the light intensity. Apart from the state filling effect Stark shift of the exciton transition and heating of the cell with QDs can cause the change of absorption and influence at the formation of transparency channel.

Two incident plane coherent waves intersecting in the cell (? - degree angle to each other is the angle between them) with colloidal solution create diffraction grating with period . Depending on the nature of the excitation (intensity, one- or two-photon resonant excitation) induced amplitude (alternating areas of transparency and opacity), phase or combined diffraction grating can arise. The transient grating technique can be interpreted in nonlinear optical terms as four-wave mixing with two collinear pump beams. Phase transient grating can be generated by spatial variations in the carrier density and due to change of refractive index with temperature.

8772-10, Session 2

Nonlinear two-photon switching by atomic coherence

Xuemei Su, Zhong Chang Zhuo, Zhuo Ren Chen, Jilin Univ. (China)

There are many important applications in nonlinear processes by using atomic coherence between a strong coupling field and multi-level atoms, for examples, storage of light pulses [1], enhanced nonlinearities at low light intensities [2, 3] and manipulation of light pulses by enhanced nonlinearities [4]. Here, we apply atomic coherence in an inverted Y-type four-level atomic system to create nonlinear two-photon switching. Considering an inverted Y-type four-level system as shown in Fig. 1, the bare atomic energy levels |1>, |2>, |3> and |4> correspond to |5S1/2, F=1>, |5S1/2, F=2>, 5P3/2 and 5D3/2 states of the hot Rb atoms, respectively. The strong coupling field is formed by two counter-propagating fields in z direction and keeps on resonance with the atomic transition |3>-|2>. When cutting off one component of the two counter-propagating fields, the coupling field is changed as a traveling wave field. Two probe fields and drive the atomic transitions |3>-|1> and |4>-|3>, respectively where the probe beam scans into two-photon resonance with the weak probe field keeping two-photon resonance .

In the equivalent dressed-state system of |1>, |2d>, |3d> and |4>, as in the dotted line diagram of Fig. 1, the atomic polarizations caused by the probe fields.

As shown in equation (1), linear resonant signal at frequency and nonlinear FWM singnal at frequency by one probe field and two-photon field are manipulated by atomic coherence induced by the resonant strong coupling field in . Two signals (i=1, 2) are generated at and in opposite directions with and , respectively. By inserting equation (1) into Maxwell wave equation.

Where i=1 or 2; jk= 31 or 43; , , , , and . Here expressions of and show that the diagonal and off-diagonal terms. According to equation (2), when is a traveling wave field, off-diagonal elements are zero, which results in electromagnetically induced two-photon transparency (EITT). With a standing wave field, off-diagonal elements in (2) are none-zero, which lead to re-absorption in two-photon bandgaps within the EITT windows. The imaginary parts of Bloch wave vector [5] versus the corresponding frequency detunings for the probe fields and can be calculated according to equ. (2) as shown in Fig. 2. The results demonstrate that nonlinear two-photon switching can be realized by a single strong coupling field.

References

[1] M. Bajcsy, A. S. Zibrov, and M. D. Lukin, Nature, 426, 638-641 (2003).

[2] Hoonsoo Kang, Gessler Hernandez, and Yifu Zhu, Phys. Rev. Lett. 93, 073601 (2004)

[3] L. Zhao, Wenhui Duan, and S. F. Yelin, Phys. Rev. A 84, 033806 (2011)

[4] Z. C. Zhuo, B. S. Ham, J. B. Kim and X. M. Su, J. of Modern Opt. 59, 46 (2012)

[5] M. Artoni, G. La Rocca, and F. Bassani, Phys. Rev. A 72, 046604 (2005)

Acknowledgment

This research is supported by National Scientific Foundation China (Grant No.11174109).

8772-11, Session 2

Nonlinearly chirped quasi-phase-matching for production of ultra-broadband twin photons

Anahit Tamazyan, Gagik Y. Kryuchkyan, Yerevan State Univ. (Armenia) and Institute for Physical Research (Armenia)

One of the challenges in the field of photonics is to design poled grating structures for frequency conversions with given spectral and temporal properties. In particular, of considerable interest is preparation of biphotons with ultrabroad spectra and extra-small correlation times in nonclassical applications such as quantum lithography, quantum optical tomography, photoemission, or quantum-information processing. Recently it was shown that these ultra-broadband biphotons can be generated in nonlinear structures with linear chirp [1, 2, 3]. Moreover it was shown that the biphoton spectra can be tailored by the characteristics of chirped structures such as the chirp parameter or the number of layers.

In this paper, we study parametric processes, particularly, production of ultra-broadband twin photons by SPDC in nonlinearly chirped layered ?(2) structures. We suggest an approach for obtaining the biphoton spectra in these media. The chirping effects are analyzed in spectra of signal and idler photons for two basic QPM configurations, which are photonic crystals and aperiodically poled crystals. The results display new important properties in comparison with the case of linear chirp.

Nonlinear chirp in photonic-like crystals: This structure consists of ?(2) layers with equal lengths in which refractive indices for the pump and the generated waves vary nonlinearly as n(j)m = n(j)0 - m^2?(j)l in each m-th layer, where n(j) is the refractive index at pump, signal or idler wavelengths (j = p, s, i), ?(j) is the second-order nonlinear chirp parameter at the j-th wavelength, and l is the length of single layer.

We have calculated the spectra for this structure with different chirp parameters and layers numbers using the suitable QPM conditions. The shape and the width of the spectra are strongly dependent on these parameters. Particularly, it has been demonstrated that for the case of small number of layers the biphoton spectra consist from resolved spectral peaks. The frequencies of the spectral lines can be controlled by the chirp parameter and temporal walk-o? between signal and idler modes.

Nonlinear chirp in aperiodically poled crystals: Our model for these structures is a layered poled crystal consisting from ?(2) layers with a nonlinear variation of lengths: the length and the second order susceptibility within the m-th layer are given by the following expressions, lm = l1 + (m - 1)^2?, ?m = (-1)^m?0, where l1 is the length of the first layer and ? is the length chirp parameter.

Our results demonstrate that for these structures broadening of biphoton spectra is stronger than for the case of linear chirp and the shape of the spectra allows generation of biphotons with smaller correlation times.

1. Magued B. Nasr et all. Phys. Rev. Lett. 100, 183601 (2008).

2. S. Sensarn, G.Y. Yin, and S. E. Harris, Phys.Rev. Lett. 104, 253602 (2010).

3. D. A. Antonosyan, A. R. Tamazyan and G. Y. Kryuchkyan, J. Phys. B: At. Mol. Opt. Phys. 45, 215502 (2012).

8772-12, Session 2

Ultra-broadband, mid IR and coherent supercontinuum generated in aperiodic chalcogenide photonic crystal fibers

Rim Cherif, Amira Baili, Mourad Zghal, National Engineering School of Communication of Tunis (Tunisia)

Recently, widely broadened supercontinuum (SC) generation has been demonstrated using ultra short pulses and photonic crystal fibers (PCF). The SC generated with this technique is a coherent ultra-wideband source that emits light from the small core of the fiber. The SC is also useful for advanced new applications, such as optical frequency combs, analytical spectroscopy, biomedical investigation and tomographic imaging applications across the mid-IR range.
We realize the flattening and extending of a low-threshold all-fiber broadband SC source based on the use of the highly nonlinear PCF (HNL-PCF) such us the As2Se3 chalcogenide PCF who exhibit high nonlinearities. The optical properties of the fundamental mode in the PCF are accurately calculated in terms of chromatic dispersion, effective mode area and nonlinear coefficient.

In this paper, a detailed of new design of As2Ss3-based chalcogenide PCF is presented by adjusting the ratio between d2 the diameter of the second ring and d1 the diameter of the inner ring surrounding the core. For the optimization of our structure we fixed ? to 1 μm and considered different ratios of d2/d1 increasing from 2.02 to 2.05 by steps of 0.1. The proposed fiber possesses an ultra-flattened dispersion curve over a wide wavelength range. The generated SC in such fiber is investigated, which has flat and smooth profile, covers a broad range. We examine the interplay of the nonlinear effects that lead to the construction of the SC as a function of the injected energy and the fiber length. We have found a bandwidth over two octaves coherent SC extending from 2 to more than 8 μm, by pumping at ?p=5 μm, 100 fs pulses with a relatively low energy of E=150 pJ in only 15 mm fiber length. Supercontinua generation was mainly attributed to the four wave mixing and the self-phase modulation. The significance of this work is that it provides a new type of mid-infrared coherent SC source with flat shape and broad band.

8772-13, Session 3

The quantum regime in tunneling plasmonics *(Invited Paper)*

Javier Aizpurua, Centro de Fisica de Materiales (Spain)

No Abstract Available

8772-14, Session 3

Coherent control of the dynamics of a semiconductor quantum dot-metal nanoparticle complex

Emmanuel Paspalakis, Sofia Evangelou, Andreas F. Terzis, Univ. of Patras (Greece)

In recent years significant interest has been given to the optical properties of complex nanosystems that combine semiconductor quantum dots (SQD) and plasmonic nanostructures, such as spherical metallic nanoparticles (MNP) and metallic nanorods. The placement of the quantum dot next to plasmonic nanostructures leads to significant alteration of the electromagnetic field felt by the quantum systems due to the interaction between the excitons from the SQD and the surface plasmons of the metallic nanostructures. This has significant influence on the optical properties of the hybrid complexes, and leads to several interesting phenomena, as for example, the creation of controlled Rabi oscillations [1,2], plasmonic meta-resonances [2], and tunable ultrafast nanoswitches [3]. In this work we analyze the potential for controlled population dynamics in a SQD–MNP hybrid system. The hybrid complex that we study is comprised of a spherical MNP and a small SQD. The SQD is described by a two-level system and the interaction of the system with an external laser field is described by the modified nonlinear density matrix equations that take into account the interaction between excitons and surface plasmons [1-4]. Here, we first show that the widely used population inversion by a π pulse method may fail for small SQD and MNP distances. We then analyze the interaction of the system with both continuous wave and pulsed electromagnetic fields and present analytical solutions of the density matrix equations, using proper approximations, that may lead to efficient population inversion in the SQD for several, even small, distances between the SQD and the MNP. In addition, we present results for high population inversion under the interaction of the system with chirped electromagnetic pulses, a method that have found various applications in the coherent control of atomic and molecular systems, and also more recently of semiconductor quantum dots. The influence of the electromagnetic pulse duration on our results is also addressed.

Acknowledgements: This research has been co-financed by the European Union (European Social Fund -ESF) and Greek national funds through the Operational Program "Education and Life-long Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: Heracleitus II. Investing in knowledge society through the European Social Fund.

1. M.-T. Cheng, S.-D. Liu, H.-J. Zhou, Z.-H. Hao, and Q.-Q. Wang, Opt. Lett. 32, 2125 (2007).

2. S. M. Sadeghi, Nanotechnology 20, 225401 (2009); Phys. Rev. B 79, 233309 (2009).

3. S. M. Sadeghi, Nanotechnology 21, 355501 (2010); Phys. Rev. B 82, 035413 (2010).

4. R. D. Artuso and G. W. Bryant, Phys. Rev. B 82, 195419 (2010).

8772-15, Session 3

Quantum dynamics of a weakly coupled nonlinear dielectric waveguide: surface-plasmon model

Evren Karakaya, Özgür E. Müstecaplıoglu, Koç Univ. (Turkey)

Quantum plasmonics is a rapidly progressing field that offers significant enhancement of weak single-photon processes and interactions by diffraction limit breaking plasmonic systems. Typically strong coupling of atomic systems with the photons can be achieved by cavity QED and circuit QED like localized systems. It is expected that surface plasmons can contribute for quantum information processing applications without any cavity. Recently we examined a system of optical fiber soliton coupled to a surface-plasmon and revealed that the metal-dielectric system is equivalent to an intrisically driven generalized Josephson junction. Our classical nonlinear dynamical analysis exhibit rich and tunable soliton - plasmon population transfer as well as localization properties. Besides, the dynamics of a dissipative photonic Josephson junction is also invastigated based on the classical theoretical model with a coupling function that depends on the soliton amplitude.

Present work aims to investigate the quantum dynamics of a weakly-coupled nonlinear dielectric waveguide-surface-plasmon system which has been formulated as a new type of Josephson junction. We developed a detailed quantum mechanical model of surface-plasmon - photon mode population dynamics by generalizing the metal-dielectric Josephson junction to the quantum regime.

We first develop a resonant plasmon-soliton interaction Hamiltonian taking into account the coupling parameter being dependent on the soliton amplitude. It is also considered that the quantum effects in a nonlinear dielectric result in an additional Kerr interaction effect due to the nonlinear polarization of the medium. This allows for the investigation of the system with intensity dependent fully bosonic Jaynes-Cummings model type coupling. We find that Heisenberg equations of motion lead to an infinite hierarchy which is decoupled and turned into a closed system in the mean-field limit.

Depending on the presence of dissipation, we also discuss the quantum treatment of the classical theoretical model in the limit of low soliton and surface plasmon amplitudes by employing the Born-Markov approximation. In particular, it is also investigated that the stochastic dynamics via master equation methods assesses the validity of mean field treatment. Initially, this equation of the system is solved for single photon case and for the vacuum state of plasmon. For single photon case, we take into account either fock state or coherent state as our quantum state. Starting from the initial conditions, we determine the presence of quantum state transfer, quantum squeezing effect, quantum coherence transfer and the quantum entanglement between soliton and surface plasmon. In addition, we present numerical solutions of these mean-field equations and underline the quantum corrections to the classical treatment. Our results could pave the path towards a full quantum mechanical treatment that should highlight quantum plasmonics beyond local enhancement of quantum coupling and bring it closer for quantum communication applications as well.

8772-16, Session 4

Nonlinear optical properties of Au nanoparticles in solution

Mónica Trejo-Durán, Univ. de Guanajuato (Mexico); Delfino Cornejo-Monroy, Univ. Nacional Autónoma de México (Mexico); Edgar Alvarado-Méndez, Antonio de Jesus Olivares-Vargas, Univ. de Guanajuato (Mexico); Julian M. Estudillo-Ayala, Univ de Guanajuato (Mexico); Victor M. Castaño-Meneses, Univ. Nacional Autónoma de México (Mexico)

Nonlinear optical phenomena research has been increased in the last years. In general, a variety of mechanisms may contribute to the nonlinearity, non lineal properties can have their origin in local and no local efects. Material of different natures can exhibit nonlocal linearities due to specific physical mechanisms, as ionic liquids [1,2], liquid crystals [3,4], films of Cu nanocrystals [5], or nanoparticles [6]. Experimental studies have suggested that the surface of nanoparticles plays a crucial role in determining their linear optical properties. In fact, a large refractive nonlocal response due to the change on the refractive index as a consequence of the heat conduction process. In this work we present the study of nonlinear optical propertiesof Au nanoparticles suspended in different solutions, using the z-scan technique, which is a sensitive and straightforward method to determine nonlinear optical properties. UV-vis spectra of this solutions with Au nanoparticles present an absorption band of around 514 nm, same as wavelength of laser used. Experimental setup was a CW argon laser with variable power, a chopper, a lens (18 cm focal lengh), cell of 2 mm and a automatic system for data acquisition. Thermal lens model [7] and Shiek-Bahae formalism [8] was used to determine the nonlinear properties. Parameters as the sign and nonlinear refractive index n2 , nonlinear absorption coefficient (beta) and dn/dt was found . Results show a nonlocal nonlinearity of thermal origin. Analysis of changes in these parameters using different solutions with the same concentration of Au nanoparticles are shown.

1. M. Trejo-Duran et al, Proc. of SPIE Vol. 8412, (2012) 84121X-1-6

2. C.E.A. Santos et al, Chem. Phys. 403 (2012) 33-36.

3. S.L. Gomez et al, Phys. Rev. E, 59(3) (1999) 3059-3063.

4. Hiu-Chi Lin et al, Opt. Comm. 283 (2010) 323-329

5. R. de Nalda et al, J. Opt. Soc. Am. B, 19(2) (2002) 289-296

6. M.H. Majles Ara et al, J. Quant. Spec. Rad. Trans 113 (2012) 366-372

7. J.P. Gordon et al, J. App. Phys. 36 (1965) 3-8

8. M Sheik-Bahae et al, Opt. Lett. 14 (1989) 955-957

8772-17, Session 4

Generation of entangled polaritons in doped media

Alexei V. Prokhorov, Igor Barinov, Sergei M. Arakelian, Vladimir State Univ. (Russian Federation)

We developed a semiclassical theory of polariton excitations for the Lambda-scheme of interaction realized in an yttrium orthosilicate crystal doped with 59Pr atoms . Canonic transformations for new type

(Raman) polaritons with specific dispersion curves for the suggested scheme have been offered. The well-known band gap between light and dark polaritons [1] in the field of a "bottle" neck vanishes and on its place coincidence of the upper and bottom dispersive branches is observed, and on the upper branch there is a characteristic minimum. It is known that the described polaritons' spectrum already was received earlier [2], but - for the two-level medium with inversion. Processes in such model are essentially non-stationary and do not allow observing this type of a spectrum experimentally. However, the condition (formulated by authors of work [2]) of strong coupling which is necessary for observation of predicted effects, was taken as a basis and, in application to the complicated three-level scheme of interaction, has allowed to prove for the first time the possibility of practical realization of such spectrum in yttrium orthosilicate crystals doped by Pr atoms.

Occurrence of a local minimum on the upper dispersion branch for polaritons with zero value of a wave vector has allowed to discuss possibility of macroscopic filling of a potential well by quasi-particles and laser generation from the given state (cf. with [3]). Capabilities of the proposed schemes can be much broader, as it comes to the generation of three-dimensional quasi-particles in the system that does not require the creation of complex layered heterostructures [3]. At the near-threshold conditions in the system the appearance of strong non-classical correlations (entanglement) between light and dark polaritons, similar to generation of biphotons in optics [4] is predicted. Thus, propagation of bright polaritons occurs in the form of Ginsburg-Pekar supplementary waves with negative group velocities [5]. Peculiarities of kinetics of quasiparticles formation depending on optical pump power are described and system transition to a "classical" mode of the laser amplifier is defined [6].

[1] J. J. Hopfield, Phys. Rev. 112, 1555 (1958)

[2] V. V. Zheleznyakov, V. V. Kocharovskii, and Vl. V. Kocharovskii, Usp. Fiz. Nauk (1989) 159 (2), 193 (1989).

[3]. P. G. Savvidis, J. J. Baumberg, R. M. Stevenson and ect., Phys. Rev. Lett., 84, 1547 (2000).

[4] D. N. Klyshko, Photons and Nonlinear Optics (Nauka, Moscow, 1980) [in Russian].. ; A. V. Burlakov, L. A. Krivitskii, S. P. Kulik, G. A. Maslennikova, and M. V. Chekhova, Opt. Spectrosc. 94 (5), 684 (2003).

[5] V. M. Agranovich and Yu. N. Gartshtein, Usp. Fiz. Nauk 176, 1051 (2006).

[6] A. V. Prokhorov, I. O. Barinov , S. M. Arakelian, Dynamic amplification and generation of entangled polaritons in doped media, Optics and spectroscopy, v. 113, #3, p.305 (2012).

8772-18, Session 5

Influence of iron doping on spatial soliton formation and fixing in lithium niobate crystals

Eugenio Fazio, Univ. degli Studi di Roma La Sapienza (Italy); Anna Maria Zaltron, Univ. degli Studi di Padova (Italy); Alessandro Belardini, Univ. degli Studi di Roma La Sapienza (Italy); Nicola Argiolas, Cinzia Sada, Univ. degli Studi di Padova (Italy)

Spatial solitons are a very attractive technique to write 3D channel waveguides inside electro-optics crystals, and in particular in lithium niobate. In fact, thanks to the very slow dielectric relaxation, solitons induce in the material channels of varied refractive index that remain modified for very long time. As a consequence, solitons can be used as a novel technique for design and realise integrated photonic circuits, whose peculiarities are neatly connected to the self-writing nature of solitons, that are able to generate channel waveguides with very low propagation losses.

Even if the dielectric relaxation of lithium niobate is very slow, soliton waveguides are not permanent and require fixing process to be stabilised in time. Fixing was previously investigated in lithium niobate to stabilize photorefractive holograms written inside, identifying mainly two techniques: a thermal fixing (i.e. to subject the in scripted crystal to a high temperature thermal treatment) or an electric fixing (i.e. to realise a rapid inversion of the bias electric field in order to invert the coercive ferroelectric field and permanently block to ferroelectric domains). Both such techniques showed undesired effects, mainly a phase-change of the written grating. Such phenomenon was attributed to an inversion of the photorefractive spatial charge field which corresponds to an inversion of the refractive index modulation as well. If such phenomenon is not critical for gratings, it is absolutely detrimental for soliton channels that become "anti-guide" instead of confining waveguides.

In such work we present alternative techniques to fix soliton channels: in particular we performed experimental tests on undoped and iron-doped lithium niobate crystals in order to fix photorefractive channels with light. Iron is considered the first source of photorefractive response; consequently iron doping would enhance the soliton formation, allowing an efficient light fixing of the written structures. We observed that an increasing of the iron concentration would result in a speeding up of the soliton formation process, both in the green and violet spectral range. Fixing was also performed using direct writing in propagation using pulsed violet high power laser beams: propagating pulses within soliton channels would cause an increase of losses due to a partial destruction of the waveguide profile, until a saturation limit above which the waveguide remains stable. We observed that such phenomenon depends on Fe^{3+} concentration within the crystals, whose increase would reduce the total light power transported by the fixed waveguide.

8772-19, Session 5

Low-power plasmon-soliton in realistic chalcogenide based planar structures

Gilles Renversez, Wiktor Walasik, Institut Fresnel (France); Yaroslav V. Kartashov, ICFO - Institut de Ciències Fotòniques (Spain) and Institute of Spectroscopy (Russian Federation); Virginie Nazabal, Univ. de Rennes 1 (France); Mathieu Chauvet, FEMTO-ST (France); Petr Nemec, Univ. Pardubice (Czech Republic)

Merging the fields of plasmonics and optical solitons attracted a lot of attention in the last decades. Devices supporting plasmon-soliton waves propagating along metal/nonlinear dielectric interfaces may be of interest for sensor applications as they offer an alternative way to couple light with plasmons. The first description of 1D stationary solution composed of a spatial soliton part coupled with a plasmonic wave was given 30 years ago. More recently, several articles have been published on this research topic of plasmon-soliton coupling (Feigembaum & Orenstein, 2007)(Bliokh et al., 2009)(Davoyan et al., 2009)(Milian et al, 2012).

Nevertheless, up to now, no experimental results have been published on this issue of soliton-plasmon coupling. The main reason is that for the already proposed structures the required induced nonlinear refractive index change (or peak power) is too high compared to the one attainable for real materials used in integrated optics.

In this work we describe planar structures made of conventional materials supporting low peak power nonlinear solutions that combine a 2D spatial soliton profile with a plasmon field.

We study the propagation of one- and two-dimensional nonlinear waves in an asymmetric 4-layer nonlinear dielectric/linear dielectric/metal planar structures made of nonlinear chalcogenide glass, silica and gold. This choice of structure and materials allows for plasmon-soliton coupling with significantly decreased light intensity (2 orders of magnitude compared to previous works).

Using vector models we compute the nonlinear dispersion relation, the field profiles, and the losses in those configurations. We design realistic structures supporting plasmon-soliton waves at low peak power compatible with current technology of chalcogenide waveguides (Nazabal et al., 2011).

To this end, we first generalize the 1D vector model proposed by Ariyasu et al. in 1985 by solving the nonlinear wave equation in each layer separately and matching the field at the interfaces using boundary conditions we obtain the analytical expressions for nonlinear dispersion relations and field shapes in our 4-layer models. Secondly, we modify the approach from Feigembaum and Orenstein to obtain the approximate 2D profile of our plasmon-soliton wave based on the solution of 1D nonlinear problem. Using optical and geometrical parameter optimization, we have found the 3 layer structure embedded in air that support plasmon-soliton nonlinear waves with realistic peak intensities (approximatively 1 GW/cm^2). These peak intensities are twice lower than the one used in 2009 by Chauvet et al. to generate a spatial soliton in a chalcogenide waveguide at 1.55 μm. The propagation losses are calculated using the conventional method based on the field shapes and the imaginary part of permittivities. The results from our semi-analytical approximate 2D model are backed up by 2D finite element method modelling of the full nonlinear structures. To achieve this task, we use an approach that we have already used to study spatial solitons in microstructured optical fibers made of Kerr materials (Drouart et al, 2008). These nonlinear solutions are obtained iteratively.

The crucial issue of the stability of the found solutions are under investigation using several numerical tools. Experimental work is also in progress.

8772-20, Session 5

Introduction of optical Newton Cradle model for understanding the N-solitons fission process under the action of higher order dispersion

Rodislav Driben, Tel Aviv Univ. (Israel) and Univ. Paderborn (Germany); Boris A. Malomed, Tel Aviv Univ. (Israel); Dmitry V. Skryabin, Univ. of Bath (United Kingdom); Alexey Yulin, Univ. of Lisbon (Portugal)

A mechanism of creating of a Newton's cradle (NC) in the form of a chain of solitons is proposed for understanding the process of high order soliton fission in optical fibers, caused by strong higher order dispersion. Beyond it's original and natural manifestation in the chain of coupled pendula, the Newton's cradle effect has found its applications in atomic, molecular, matter waves and quantum physics. In optics the effect is manifested by strongest soliton motion through the chain of other solitons or localized light peaks by experiencing quasi-elastic collisions. In case of N-soliton fission process, after the initial compression stage of the input N-soliton into a chain of fundamental quasi-solitons and emission of dispersive waves, the tallest soliton advances along the chain through the elastic collisions with other solitons, and then escapes. The power and momentum of the soliton is gradually transferred through the chain, followed by a new soliton ejection from the chain with different frequency. Direction of the power transfer is determined by the effective sign of the high-order dispersion. The remaining chain of fundamental quasi-solitons continues propagation in a bound state. Increasing, the soliton order of the input pulse makes it possible for multiple solitons ejected with different frequencies. This effect of multi-soliton ejection along with dispersive waves out of initial N-soliton with very high values of N strongly manifest itself in broadband supercontinuum generation. The effect of the cradle is little effected by the higher order nonlinearities such as Raman and self-steepening. The work paves a way to study the effect of NC in various periodic light structures with a source of asymmetry. For example fundamental solitons chains, Airy pulses in strong nonlinear regime, arrays of discrete solitons can be considered.

8772-21, Session 5

The optical control of spatial dissipative solitons in optical fibers filled with a cold atomic gas

Alexei V. Prokhorov, Mikhail Gubin, Andrei Y. Leksin, Vladimir State Univ. (Russian Federation); Maxim G. Gladush, Institute of Spectroscopy (Russian Federation); Sergei M. Arakelian, Vladimir State Univ. (Russian Federation)

We consider the problem of formation and all-optically control of optical vortex solitons for Lambda-scheme of Raman-type interaction, taking into account the local field effects and atom-field perturbations. Recently fabricated hollow-core photonic-crystal fiber loaded with cold atoms [1] may be considered as a promising medium for the formation of soliton regimes. The coherent optical control by pump beam in such an atomic medium leads to effective development of dynamical equilibrium of dispersive-diffraction, nonlinear and dissipative processes that are necessary to stabilize dissipative solitons.

The self-consistent problem of nonlinear scattering of the probe field in a dense atomic medium of three-level atoms has been analyzed using the adiabatic approximation, which makes it possible to reduce the problem to solving a fifth-order nonlinear Ginzburg–Landau equation (GLE). Using variation methods and direct numerical simulation for GLE we have predicted the regions of the parameters of the medium and fields at which optical vortex solitons can be efficiently formed in a model of a hollow-core fiber filled with a gas of 87Rb atoms. Accounting of the dipole-dipole interactions in such a problem has a stabilizing effect on the formation of dissipative solitons. However, at the accounting of initial azimuthal perturbations [2] of optical vortices there appears a 'fine' structure in the form of separate regions of stability for solitons with modified forms or regions, where the optical vortices decay. The switching between various forms of solitons in the considered scheme can be simply realized by management of pump beam intensity.

We have considered the problem of controlling the dynamics of optical vortex solitons obtained while following the conditions for Raman regime of interaction scheme, which do not violate their stability. We have shown that modulation of intensity of the pump laser inside of region of stability of the spatial dissipative solitons of probe beam allows to change effectively their group velocity and to observe the optically-induced transitions between structures of various topologies. We have offered [3] to observe the predicted effects by using the model of thin hollow-core gas-filled fiber being developed in articles [4] which allows to create atomic Bose-Einstein condensate in oblong system.

1.Bajcsy M., Hofferberth S., Peyronel T., Balic V., Liang Q., Zibrov A.S., Vuletic V., Lukin M.D. Phys. Rev. A, 83, 063830 (2011).

2.Skarka V., Aleksic N.B., Leblond H., Malomed B.A., Mihalache D. Phys. Rev. Lett., 105, 213901 (2010).

3.M.Yu. Gubin, A.V. Prokhorov, M.G. Gladush, A.Yu. Leksin, S.M. Arakelian, Formation and optical control for dissipative vortex solitons in bec-filled hollow-core optical fibers, Quantum Electronics, v.42, p.616 (2012)

4.Balykin V.I., Laryushin D.V., Subbotin M.V., Letokhov V.S., Pis'ma Zh. Eksp. Teor. Fiz., 63 (10), 763 (1996).

8772-22, Session 6

Attosecond electron synchrotron on a nanoscale *(Invited Paper)*

J. Mikhailova, Max-Planck-Institut für Quantenoptik (Germany)

No Abstract Available

8772-23, Session 6

Non-maxwellian electron distribution in time-dependent simulation of low-Z elements iluminated by a high intensity X-ray laser

Alberto G. Garcia, Pedro Velarde, Univ. Politécnica de Madrid (Spain); François de Gaufridy, Univ. Politécnica de Madrid (Spain) and Czech Academy of Sciences (Czech Republic); Manuel Cotelo, David Portillo, Alfonso Barbas, Augustín I. González, Univ. Politécnica de Madrid (Spain); Philippe Zeitoun, Ecole Nationale Supérieure de Techniques Avancées (France)

A time-dependent collisional-radiative model and non-maxwellian electron distribution solver is implemented to study radiation transport in matter from ultrashort and ultraintense X-ray bursts. The electron distribution, used for computation of collisional rates in the colllisional-radiative system, is obtained in the Fokker-Planck approach with additional inelastic terms. The collisional-radiative model includes shakeoff processes calculated in the sudden aproximation.

8772-24, Session 6

Experimental study of a crystalline-resonator based optoelectronic oscillator

Patrice Salzenstein, Aurélien Coillet, Rémi Henriet, Laurent Larger, Yanne K. Chembo, Ctr. National de la Recherche Scientifique (France)

In this work, we present experimental results on an optoelectronic resonator (OEO) based on intensity modulation and a high-Q disk resonator. In our configuration, the crystalline whispering-gallery-mode resonator acts both as a frequency filter, selecting the microwave oscillating frequency, and as an optical storage element. In such a system, the oscillating frequency corresponds to the free spectral range of the resonator (between 10 GHz and 11 GHz), and therefore no delay-induced spurious peaks are present in the spectrum, in contrast to the case of the classical optoelectronic oscillator where the storage element consists of an optical fiber delay line. An other advantage of our system resides in its compactness allowing for efficient control of the temperature. The optical resonator presents a quality factor in the range of 5.10^8 to 10^9 measured by cavity ring down method. The OEO delivers a unique peak at 10.5 GHz with a stable +5 dBm microwave power to be characterized in terms of phase noise. Details results and description are to be presented at the conference.

8772-25, Session 6

Nonlinear self-reflection of intense ultra-wideband femtosecond pulses in optical fiber

Leonid Konev, Yuri A. Shpolyanskiy, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

We consider propagation of intense few-cycle pulses in single-mode optical waveguides. Standard theoretical approach employs assumption of unidirectional pulse propagation in waveguide. It means that only wave with forward-directed energy flux is considered, but backward wave is ignored. However the latter is inherently generated via medium nonlinear response even if it was not present initially (nonlinear self-reflection). Here we present method for numerical simulation of pulse propagation with account of forward- and backward-propagating waves based on solution of set of first-order equations analogous to the full wave equation.

Our analysis and numerical simulations show that a solution of the equation for backward wave consists of two parts. One propagates backward, as it was expected, while the other, surprisingly, propagates forward together with the forward wave being tightly coupled with it: the electric field structure is imposed by the forward wave via nonlinear medium response. The presence of additional forward-propagating field originates from boundary conditions and arbitrariness of splitting total field into a sum of forward and backward waves. The field structure of backward wave is simulated in details. Having been formed due to nonlinear interaction with the forward wave, it further runs away independently in backward direction in considered regimes.

Spectral content of forward and backward waves is also analyzed. Being extremely short in time (~10-20 femtoseconds) the input pulse has ultra-wideband spectrum, which broadens further during propagation with generation of supercontinuum. Third harmonics appear in spectra of forward and backward waves due to third-order nonlinearity. The additional forward-propagating field also transforms into supercontinuum.

It is also shown that if simplify original set of equations by neglecting less-important terms over distances in the order of few wavelengths, it is possible to get analytical solution for the process of backward wave generation. It allows us to derive analytical expression for the amplitude of the backward wave, which perfectly matches our simulations. It can serve as the analytical estimate for the intensity of backward wave, which was not known before to the best of our knowledge.

8772-26, Session 6

A high efficiency wavelength conversion scheme based on four-wave mixing in semiconductor optical amplifier utilizing ASE broadband source at ultrahigh 1000Gbs data rate

Osayd M. T. Kharraz, David I. Forsyth, Univ. Teknologi Malaysia (Malaysia)

Spectrum slicing technique employing incoherent light is an economic, practical and therefore attractive solution for future all-optical networks, especially for wavelength-division multiplexing (WDM) transmission systems. We present a high efficient performance of a NRZ SOA-based FWM wavelength converter system utilizing polarized Erbium doped fiber ASE source and pump source at 240 Gb/s that has no need of probe laser light source. The sliced wavelength from ESA source is converted into any wavelength using this technology. The entire erbium doped fiber amplifier noise spectra is exploited in this wavelength converter. Inherent noise arises from spectrum slice system is counted as one of the most adverse phenomenon on such system performance. With recourse to FWM mechanism in SOA we successfully suppress the resultant intensity noise from the implemented EDFA broadband source. We show that wavelength shift spans of 2 nm up to 90 nm (1508 nm to 1598 nm range) are possible whilst still maintaining 12 dB and 25 dB OSNR as minima in both up and down wavelength conversion. The conversion efficiency and optical SNR of the converted signal both decrease at large detuning wavelengths. In contrast; these two figures of merits are boosted as the device current is raised from 100 mA to 500 mA. The impact of varying the input pump power on the conversion efficiency and OSNR is also investigated. The wavelength converter is modeled and simulated using Optisystem software.

8772-27, Session 7

Silicon nitride waveguide with flattened chromatic dispersion

Jose Manuel Chavez Boggio, Daniel Bodenmüller, Tino Fremberg, Leibniz-Institut für Astrophysik Potsdam (Germany); René Eisermann, Leibniz-Institut für Innovative Mikroelektronik (Germany); Roger Haynes, Martin M. Roth, Leibniz-Institut für Astrophysik Potsdam (Germany)

Multi-cladding-layer silicon nitride waveguides were fabricated with thicknesses and refractive indices optimized to provide flat and low chromatic dispersion in the near infrared. Two different cladding structures were proposed and investigated: in the first one, two cladding layers made of doped Si_3N_4 and having a slightly slower (decreasing) refractive index than in the un-doped Si_3N_4 core are sandwiched between the core and the main silica cladding. The thickness of the extra cladding layers is 200 or 400 nm, while the core has a thickness of 750 nm and variable width. In the second structure, for the two extra layers we add first a silica cladding and then a Si_3N_4 cladding, which are sandwiched between the Si_3N_4 core and the main silica cladding. To measure the dispersion of these waveguides with engineered refractive index, we used a low coherence interferometer setup. A second interferometer using a He-Ne laser was coupled to the first one to accurately calibrate it. This allowed us to measure low dispersion values in very short waveguides (between 2.4 and 4.3 cm in length). We demonstrate that the dispersion ripple is reduced by a factor of ten when measured between 1.2 and 1.8 microns if compared with a waveguide where the two extra cladding layers were not added. The propagation losses of the engineered waveguides were also characterized. Our findings demonstrate that the chromatic dispersion can be precisely controlled in CMOS compatible integrated waveguides at a level previously only reached in photonic crystal fibres. New avenues are open for non-linear based devices on a chip

8772-28, Session 7

Numerical model for DGD estimation in optical transmission system

Ján Litvik, Daniel Benedikovic, Univ. of Zilina (Slovakia); Marc Wuilpart, Univ. de Mons (Belgium); Milan Dado, Michal Kuba, Univ. of Zilina (Slovakia)

In this paper we investigate the nonlinear and polarization effects in optical transmission systems and its influence on transmitted pulses. The main attention is focused on fundamental description of refractive index in nonlinear birefringent environment. In general, the optical fiber is a nonlinear transmission medium. The mutual interaction between transmission medium and optical intensity induces changes in the refractive index resulting to the nonlinear effects that can be polarization-dependent in presence of birefringence. The global effect has a significant impact on pulse propagation. The aim of this paper is to present a numerical model, which will be suitable for estimation of DGD (Differential Group Delay) parameter in nonlinear birefringent medium. The DGD is crucial for evaluation of the impact of PMD (Polarization Mode Dispersion) in high-bit-rates fiber-optic system. Our approach opens the novel opportunity for DGD estimation based on numerical model of optical pulse propagation in nonlinear birefringent medium. Numerical model is based on solving NLSE (Nonlinear Schrodinger Equation) through the SSFM (Split-Step Fourier Method). The model is compatible for various input parameters, different kinds of optical fibers and also for different types of modulation formats. The obtained results show the DGD for different system parameters (such as input power and the wavelength) and for different fiber polarization characteristics (birefringence and mode coupling). The total pulse broadening is also calculated and illustrates how all degradation effects influence the performance of fiber-optic transmission system.

8772-29, Session 7

Double-frequency Brillouin fiber lasers

Andrei A. Fotiadi, Faculté Polytechnique de Mons (Belgium) and Ioffe Physico-Technical Institute (Russian Federation) and Ulyanovsk State Univ. (Russian Federation)

Single-frequency Brillouin fiber lasers are very promising for many applications, such as coherent optical communication, interferometric sensing, coherent radar detection, and microwave photonics. Brillouin lasers with doubly-resonant cavities exhibit low power threshold, high spectral purity and low intensity noise. In such lasers Stokes wave is generated by a short fiber ring cavities that are simultaneously resonant for pump and Stokes radiation. However, such cavity design makes laser operation extremely sensitive to any variations of the fiber cavity length. Therefore, Brillouin lasers are commonly equipped by complicated active stabilizing systems.

Here we report two new and completely passive solutions enabling perfect stabilization of the Brillouin lasers with doubly-resonant cavities. In our experiments, the first laser configuration was stabilized through self-injection locking mechanism implemented to the laser cavity with DFB semiconductor pump laser. Second configuration comprises a nonlinear fiber mirror based on the population inversion dynamical gratings induced in low-absorbed Er-doped fiber. In both cases, once the pump laser gets a resonance with the ring laser cavity, the growing optical feedback pushes the DFB pump laser (in the first case) and the nonlinear fiber mirror (in the second case) to operate the cavity resonance frequency. After such locking any slow detuning of the cavity resonance, for example, caused by temperature variations is compensated by corresponding detuning of the pump laser operation wavelength. As a result the operation wavelength of the pump laser occurs to be locked to the ring resonance frequency leading to effective generation of Brillouin Stokes radiation. In our experiment the pump-to-Stokes conversion efficiency of ~40% and the Stokes linewidth of <500Hz in the first case and < 100Hz in the second have been successfully demonstrated with the laser configurations.

Dynamical pump and Stokes power behaviors are similar in both cases. Stable power behaviors are observed during long time intervals which are interrupted by short-time jumping. The time behavior of the pump and the Stokes radiation is strongly correlated. Jumps of the pump power are followed by Stokes power fluctuations and vice versa. However, the pump power continue to keep such behavior below the Brillouin threshold, when the effect Stokes radiation on the laser dynamics is negligible. The duration of the stable intervals depends on environment noise and could be increased by noise protection of the laser. The stable time intervals of 0.2 – 1 sec are typical for unprotected laser in common lab environment. We believe that the laser stability can be further improved by utilizing of fully PM fiber spliced configuration.

8772-30, Session 7

Tunable multiwavelength quantum dot external-cavity lasers

Gray Lin, Chen-Hung Pai, National Chiao Tung Univ. (Taiwan)

Tunable dual-, triple- and quadruple-wavelength light emitters based on InAs/InGaAs/GaAs quantum dots (QDs) are demonstrated in this study. The chirped multilayer QD gain media are arranged in Fourier-transform external-cavity laser (FT-ECL) setup, i.e. modified Littman configuration with lens and slit introduced in the first-order diffracted path. Novel slit design with 2, 3, and 4 slits select different wavelengths that are diffracted from the grating for optical feedback. Therefore, the dual-, triple- and quarduple-wavelength ECLs are implemented for numerous applications, such as wavelength-division multiplexing (WDM) in fiber-optic communications and terahertz (THz) light sources generation by difference-frequency generation (DFG) mechanism.

The solitary laser diodes are processed to 5-um ridge width and cleaved into 1.5-mm length, and then anti-reflection (AR < 1%) coated in front facets and high-reflection (HR > 98%) coated in back facets. The resulted multi-wavelength lasing emissions are achieved under injected current of 100 mA (or 1.33 kA/cm2). Around peak-gain wavelength of 1250 nm, the adjacent wavelength separation is up to 13 nm for triple-wavelength lasing emissions, and about 4-5 nm for quadruple-wavelength lasing emissions. The maximum wavelength separation is limited by our slit design while the minimum wavelength separation is determined by the slit width. Moreover, the side-mode suppression ratio is over 20 dB. Application of coarse-WDM or even dense-WDM can be benefited from further optimization.

The dual-wavelength lasing emissions are low in lasing threshold and widely tunable over 50 nm; however, the spatial separation of emitted wavelengths could be too large to have efficient optical feedback. Therefore, two separate external mirrors are adopted to extend the wavelength separation. The achieved maximum wavelength separation is over 86 nm or 17 THz in frequency separation, which is also limited by our slit design. The dual-wavelength ECLs are promising candidate for THz generation by DFG mechanism using photomixer or nonlinear crystal. We will present the continuous-wave THz generation in the meeting.

8772-31, Session 7

The analytical model of ground-state lasing in broadband semiconductor quantum dot lasers

Vladimir V. Korenev, Artem V. Savelyev, Alexey E. Zhukov, Alexander I. Omelchenko, Saint Petersburg Academic Univ. (Russian Federation); Mikhail V. Maximov, Ioffe Physico-Technical Institute (Russian Federation)

Long-wavelength InAs/InGaAs QD lasers emitting via QD ground state (GS) optical transitions (? ~ 1.3?m) are the promising light sources for a wide range of practically important applications: from medicine to ultrafast information transfer. Moreover, these lasers operating in multi-mode regime can be a beneficial alternative to the currently used arrays of DFB-lasers (distributed feedback lasers) due to the simplicity of fabrication. However currently existing models of these lasers can give only the quantitative description of their operation. In its turn, this makes the process of further analysis and finding of the key parameters of spectral characteristics of QD laser more complicated.

We have built a theoretical model, which allows one not only to describe the experimental data quantitatively, but also to obtain the analytical expressions for the main spectral characteristics of QD lasers, taking into account inhomogeneous broadening. In particular, the analytical expressions, describing shape and width of lasing

spectrum and the shift between the density of states maximum and maximum of lasing spectrum were obtained. The example of optimizing of such a laser by using active layer with intentionally introduced irregularity was also considered in details.

8772-32, Session 7

Cascaded carbon monoxide laser frequency conversion mid IR range in a single ZnGeP2 crystal

Igor O. Kinyaevskiy, P.N. Lebedev Physical Institute (Russian Federation)

Collinear two-stage frequency conversion of CO laser radiation in a single nonlinear crystal ZnGeP2 was demonstrated. Cryogenic low-pressure CO laser that simultaneously operated on ~150 ro vibrational transitions in the wavelength range from 5.0 to 7.5 microns, which corresponds to the frequency interval more than a half octave, was applied to pump the crystal. The repetitively pulsed CO laser operated in Q-switch mode with rotation mirror, pulse repetition rate was from 30 to 130 Hz, laser pulse duration was of 1 ?s with peak power up to 4 kW. The ZnGeP2 crystal was installed at 48 degree entrance phase-matching angle. In the first stage of the frequency conversion about 350 spectral lines in the wavelength range from 2.5 to 3.7 microns were observed due to the second harmonic and sum-frequency generation by ee-o type. The external and internal efficiency of this frequency conversion of fundamental lines to was 1.8% and 3.5%, respectively. Maximum power of sum frequency radiation was near a wavelength 2.5 µm. In the second stage of the frequency conversion about 90 spectral lines in the wavelength range from 4.3 to 5.0 microns and more than 80 lines in the range from 7.5 to 8.3 microns were observed due to the difference frequency generation of the lines obtained in the first stage of the frequency conversion and fundamental CO laser lines. This second stage was possible because of different frequency generation realized at the same entrance phase-matching angle. The external and internal efficiency of frequency conversion of fundamental lines to different frequency lines within from 4.3 to 4.9 ?m range was 0.25% and 0.48%, respectively. A computer simulation indicates full cover of the spectral range of 2.5 to 10 ?m by this collinear two-stage frequency conversion in one nonlinear crystal ZnGeP2 of CO laser emission. Thus, on the basis of a single nonlinear crystal ZnGeP2 pumped by one CO laser, a broadband laser source (with frequency range covering more than one-and-half octave), operating simultaneously on ~670 spectral lines in the wavelength range from 2.5 to 8.3 microns, was developed.

8772-43, Session 7

Bulk dipole contribution to second harmonic generation in diamond lattices

Hendradi Hardhienata, David Stifter, Kurt Hingerl, Johannes Kepler Univ. Linz (Austria)

The recent high interest in surface science techniques capable to probe surfaces in-situ has renewed the interest in linear and nonlinear optical techniques such as second harmonic generation (SHG). This interest has been accompanied by theoretical efforts to model the measured data, interpreting them either in a classical picture or taking into account quantum mechanics by involving transitions between initial and final states.1 Especially for SHG the interpretation and the origin of the data is controversial. Some authors2 claim that part of the SHG response arises from the surface and bulk quadrupoles or from magnetic dipole effects, whereas others3 are mainly considering surface contributions. To our knowledge, however, all the literature has up to now neglected bulk dipole transitions in materials with inversion symmetry4,5 using the following argument: Materials with inversion symmetry are described by potentials with even powers of the coordinates (i.e. ~r2, ~r4, etc.). Because a second harmonic contribution providing response to an incident field oscillating with frequency ! could origin, due to inversion symmetry, only from forces which are quadratic, or potentials which are cubic in a component of ~r, this effect has been directly excluded.

To our knowledge it has never been discussed in the context of SHG that the potential of atoms in the diamond structure is, due to their tetrahedral bonding, intrinsically inversion asymmetric. This asymmetry can be observed, e.g., by plotting the potential within in the (111) plane - i.e. in the plane of the polarization of the driving field- as equi-contour plot. (Fig.1c).

FIG. 1: a) The incoming electric field decays along the propagation direction. b) Layers are shown where one Si atom (Si(1)) is covalently bound to one from above and to three Si atoms underneath, where one is called Si(2). The center of inversion symmetry (CIS) is located in the middle between Si(1) and Si(2). c) Contour plot of the ab-inito potential for Si in the (111) plane (VASP calculation). Si(111), respectively its atoms, can be described in a simple picture by four equivalent covalent bonds with a sequence of layers, which are alternatingly bound by one up bond or by three down bonds to the next layer (see FIG. 1b). For our model it is insignificant, if we imagine the bonds either as rigid, such that the electrons can only move along the bond direction6 or as sp3-hybridized orbitals7, or as extended coherent wavefunctions, describing the probability density for finding the electron in a given spatial interval. Because the exciting field decays along z due to absorption when penetrating into the bulk, the nonlinear radiation of the Si(1) atom is not fully canceled by the radiation of the deeper in the bulk positioned atom Si(2), because this atom experiences a lower field. So, in the antenna picture for the Si (111) case the two waves, originating at Si(1), respectively Si(2) do not fully destructively interfere. It has to be mentioned that even for the case that the photon energy is smaller than half the bandgap, the occurrence of SHG implies absorption of the linear wave. This effect occurs at each bilayer and can be analytically summed. Finally we propose an experiment, exploiting the different dispersion for the fundamental as well as frequency doubled radiation to determine this effect.

1 J. F. McGilp. Journal of Physics: Condensed Matter, 22(8):084018, 2010.

2 P. Guyot-Sionnest and Y. R. Shen. Phys. Rev. B, 38:7985–7989, 1988.

3 M. Corvi and W. L. Schaich. Phys. Rev. B, 33:3688–3695, 1986.

4 R. W. Boyd. Nonlinear Optics. Academic Press, 2003.

5 Y. R. Shen. Nature, 337:519–525, 1989.

6 G. D. Powell, J.-F. Wang, and D. E. Aspnes. Phys. Rev. B, 65:205320, 2002.

7 J. E. Mejia, C. Salazar, and B. S. Mendoza. Revista Mexicana de Fisica, 50(2):134–139, 2004

8772-33, Session 8

DNA: a nonlinear material for green photonics *(Invited Paper)*

Valentin I. Vlad, National Institute for Lasers, Plasma and Radiation Physics (Romania)

No Abstract Available

8772-34, Session 8

DNA translocation through a periodically patterned nanoprobe

Seong Soo Choi, Myoung Jin Park, Sun Moon Univ. (Korea, Republic of); Namkyoo Park, Seoul National Univ. (Korea, Republic of); Seung Min Park, Luke P. Lee, Univ. of California, Berkeley (United States)

The Al nanoapertures surrounded by periodic patterns on the pyramidal structures were fabricated. The nanometric size aperture with ~ 100 nm diameter surrounded by equidistant elliptic groove patterns presented greater transmission than the aperture with circular groove patterns. The translocation of ?-DNA through these fabricated nanostructures was examined. We observed the strong optical signal from the translocated DNA through the nanopore surronded by the periodically patterned sample.

8772-35, Session 8

Application of layered graphene for solid state laser mode-locking in the near-infrared

Uwe Griebner, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Elena Ugolotti, Univ. degli Studi di Pavia (Italy); Andreas Schmidt, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Jun Wan Kim, Dong-Il Yeom, Fabian Rotermund, Ajou Univ. (Korea, Republic of); Sukang Bae, Byung Hee Hong, Seoul National Univ. (Korea, Republic of); Xavier Mateos Ferre, Francesc Díaz, Univ. Rovira i Virgili (Spain); Antonio Agnesi, Univ. degli Studi di Pavia (Italy); Valentin P. Petrov, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Graphene is experiencing an increasing level of interest as saturable absorber for mode-locking of fiber and bulk lasers owing to its unique optical and physical properties. Like other carbon nanostructures such as single-walled carbon nanotubes (SWCNTs), it exhibits a very fast recovery time and can be fabricated by relatively simple processes. Graphene has the great advantage over SWCNTs that it exhibits an ultrafast saturable absorption over an ultrabroad spectral range without bandgap engineering.

Here we report nonlinear characteristics of layered graphene near 1.0 and 1.5 µm. High-quality graphene layers were fabricated by the chemical vapor deposition technique. Mono- and bilayer graphene were transferred to 1-inch quartz substrates and successfully applied as saturable absorbers for femtosecond bulk laser mode-locking.

The linear loss of the monolayer graphene approaches almost the theoretical value of 2.3% - which indicates its high quality - and nearly doubled for the bilayer graphene in the spectral range considered. The measured pump-probe traces delivered an instantaneous response of about 200 fs limited by the pulse duration of the excitation source and a slow 1/e recovery time of about 1.5 ps, nearly independent on the operation wavelength. From the data of the nonlinear transmission change, a slight decrease of the modulation depth and the saturation fluence with increasing wavelength is observable. The extracted values are well-suited to achieve stable mode-locking of typical bulk lasers.

Employing the monolayer graphene sample, a passively mode-locked Yb:KLu(WO4)2 laser delivered sub-200 fs pulses with output powers of up to 160 mW at 1045 nm. Pulses shorter than 90 fs were also recorded under slightly different conditions but the steady state regime could not be stabilized. We attribute these instabilities (mainly double pulsing) to the low modulation depth of the monolayer graphene SA, which amounts to 0.75%. A more stable operation is expected by choosing the bilayer graphene SA due to the nearly doubled modulation depth. The diode-pumped mode-locked laser results are comparable to those demonstrated with the same Yb-laser gain medium using SWCNTs as saturable absorber.

8772-36, Session 9

Reflection and propagation of laser pulse with a few cycles in medium with time-dependent dielectric permittivity

Vyacheslav A. Trofimov, Ivan V. Mishanov, Lomonosov Moscow State Univ. (Russian Federation)

On the base of computer simulation we investigated a propagation of femtosecond laser pulse in a linear medium with dielectric permittivity modulated in time. We showed that in dependence of the relation between curried frequency of wave packet and the modulation frequency for medium the various phenomena take place: frequency up conversion, decay instability, slow light and faster light at definite frequencies of appeared laser pulses. We investigated also light localization in such time-dependent structure. We believe that considering scheme of laser pulse interaction with medium can be used in processing of data by optical methods, for example

8772-37, Session 9

Spatial localization of microwave pulse energy in a layered linear medium containing metamaterial in some layers

Vyacheslav A. Trofimov, Evgeniy V. Trykin, Lomonosov Moscow State Univ. (Russian Federation); Sergey I. Tarapov, Sergey V. Nedukh, Usikov Institute of Radiophysics and Electronics (Ukraine)

Using computer simulation we investigated a propagation of microwave laser pulse in a linear layered medium containing metamaterial in some layers. Such layers can be considered as defects of the layered structure. Therefore, a localization of the microwave energy can take place. We investigate an influence of a number of layers with metamaterial on the microwave energy localization, energy transmission and energy reflection from the structure with limited number of layers.

The other investigated problem is a transmission of a microwave pulse with carried frequency belonging the forbidden zone of frequencies through the considered layered structure.

8772-38, Session 9

Numerical investigation of the Gaussian pulses propagating in optical fibers with refractive indices stochastically changed due to environmental conditions

Libor Ladányi, Róbert Menkyna, Jarmila Müllerová, Univ. of Zilina (Slovakia)

Current optical communication systems have been usually deployed in different physical environments. All environmental conditions have different physical characteristics that can significantly influence transmission properties of these systems. In this article, we focus on changes in possible temperature and mechanical stress and their effects on the refractive indices of optical fibers and their transmission characteristics. Especially we discuss the impact of the stochastic changes in susceptibilities and consequently nonlinear effects occurring in optical fibers and influencing the propagation of optical pulses.

As input pulses the Gaussian pulses of intensities exceeding intensities of atomic electric fields in the fibers have been taken into account. For such pulses the refractive index changes can become nonlinear, especially in case when considerable environmental changes of temperature and mechanical stress can occur. The numerical studies of the pulse propagations in such nonlinear environmental conditions have been performed in this article.

The results have been obtained by solving the nonlinear Schrödinger equation by the so-called method of lines, a specific numerical method belonging to the group of finite-difference methods.

8772-39, Session 9

Two-photon polymerization of diacrylate mesogens for producing polymer with patterned orientation structures

Wenjun Zheng, Wei-Zhe Huang, National Sun Yat-Sen Univ. (Taiwan)

Two-photon absorption (TPA) is a quantum process in which two photons of identical or different frequencies are absorbed simultaneously to excite a molecule form one energy state to a higher-energy state. The quadratic intensity dependence of TPA for an incident beam of wavelength ? allows the TPA process to be confined to a volume of order of ?3 at the focus. The use of a long-wavelength beam allows the TPA process to occur deeper into the volume. These distinctive features make TPA a truly stereoscopic technology for activating chemical or physical processes within a localized position

with high resolution in three dimensions. Therefore, materials that possess desired electronic energetic structures and allow two photon absorption to occur have drawn massive attraction. On the other hand, to produce materials with local orientation structures is meaningful for producing functional photonic materials. Our attention was caught by diacrylate mesogens for their excellent photochemical activity and usefulness in electro-optical devices.

Recently, we studied photon absorption process in acrylate-based mesogens. The materials used were diacrylate compounds RM82 and RM257, both were purchased from Merck. Both mesogens show very large two photon absorption coefficient to a long wavelength irradiation, and thus two photon absorption process in the diacrylate mesogens can be trigged by a low-power laser beam. In the present study, two photon absorption in the diacrylate mesogens has been observed for a low-power continuous laser irradiation at 632.8 nm wavelength. The two photon absorption coefficient is quite sensitive to the molecular ordering of the mesogen. The mesogens exhibit a larger two photon absorption coefficient in the nematic phase than in the isotropic phase. This indicates that the molecular ordering of the mesogen of the liquid crystal may provide the cooperative effects that can enhance optical and/or nonlinear optic effects.

Due to their anisotropic nature the mesogenic groups in the diacrylate mesogen can be aligned by an external field. The polymerization of diacrylate monomers results in the formation of densely crosslinked networks. Therefore, it is possible to produce a polymer with local orientation structures. In this study, the crosslinking of diacrylate was initiated in a holographic grating pattern created using two-beam-interferometry. The holographic field provides both the driving force for the alignment of mesogenic groups in the diacrylate mesogen and the energy for producing free radicals for crosslinking of diacrylate groups. As a result, oriented polymer network was produced locally in the diacrylate mesogen, and the orientation structures were frozen by the polymerization of the mesogen. The orientation of the network was found to be perpendicular to the interferometric fringes.

These results indicate that diacrylate mesogens are promising material for two-photon process. Two-photon absorption induced in situ polymerization can be a useful means to produce polymer with local orientation structures.

8772-40, Session 9

Laser beam bending cylindrical gradient curved lens under atmospheric conditions

Remzi Yildirim, Gazi Univ. (Turkey)

optoelectronics component, lens, application of laser

8772-41, Session 9

The role of MgO and CuO on the optical properties of lithium potassium borate

Yasser Alajerami, Univ. Teknologi Malaysia (Malaysia) and Alazhar Univ. (Palestinian Territory, Occupied); Suhairul Hashim, Wan Muhamad S. Wan Hassan, Ahmad Termizi Ramli, Univ. Teknologi Malaysia (Malaysia)

Optical properties of Lithium Potassium Borate (LKB) co-doped with CuO and MgO are reported for the first time. Previous study proved the efficiency of copper to improve the optical properties of glass network. Monovalent copper is one of the best-known activators of efficient luminescence owning to its transition (3d9 4s1 ? 3d10). In this work, a sample doped with 0.1 mol % copper (CuO) and X mol % of magnesium oxide (MgO) was prepared by quenching chemical technique. The X-ray Diffraction (XRD) technique showed the amorphous structure of the sample. An energy transfer up-conversion phenomena is obtained by exciting the current samples with 650 nm. The emission spectra provided a broad shoulder and two prominent peaks at 504 and 540 nm, respectively. The strongest intensity (~710 a.u.) was observed when we added 0.1 mol % of MgO and Cu ions to the glassy sample. This enhancement is contributed to the energy transfer from Mg2+ ions to monovalent Cu+ ion. It is well known that magnesium oxide alone generates weak emission intensity, but during this increment the MgO act as an activator (co-doped) for Cu ions.

Finally, energy band gap, density, ion concentration, molar volume, Polaron radius and inter-nuclear distance all were measured for the current samples. The new host showed non-linear optical relation, which promises to be useful for future optical and electrooptical devices related to telecommunications, optical storage, and all-optical computing disciplines.

According to our literature review, these results are being reported for the first time on Li2CO3- K2CO3-H3BO3 The current results confirmed the assumption that magnesium act as a luminescence activator for photoluminescence process. The adding of Mg2+ ions also leads to an increase in the host vacancies that act as new excitation centres for Cu ions.

In the present study, three photoluminescence schemes were designed to identify the effect of CuO and MgO on the emission of our glass system. The first scheme determines the PL spectra of LKB doped with 0.1 mol% copper. The second scheme illustrates the PL spectra of LKB doped with 0.1 mol% magnesium oxide. The last scheme shows the PL spectra of LKB doped with 0.1 mol% CuO and different concentration of MgO. All spectra were obtained under the excitation of 650 nm wavelength light, and the scale ranged from 300 to 900 nm.

8772-42, Session PS

Determination of the uncertainty for phase noise delivered by an optoelectronic based system

Patrice Salzenstein, Ekaterina Pavlyuchenko, Ctr. National de la Recherche Scientifique (France)

The aim of this work is to determine the uncertainty on phase noise results obtained by using a double delay line optoelectronic system operating at 1.55 µm wavelength and designed for microwave photonics applications. This system has two symmetric arms to uncorrelate the propagation of the optic signal through the instrument developed. It works for any microwave signal in X-band. The use of cross-correlation increases the noise floor of the system as lower as -170 dBc/Hz at 10 kHz from the 10 GHz modulation signal of the 1.55 µm wavelength. We present how the phase noise is determined and how the global uncertainty of this system is calculated according to the main guideline delivered by the Bureau International des Poids et Mesures (BIPM). According to the BIPM guideline, we first examine statistic contribution such as repeatability and experimental standard deviation are the main contributors. Elementary term of uncertainty for repeatability is found to be up to 0.7 dB at 1 sigma at some Fourier frequency. Other elementary terms still have lower contributions. For instance, temperature effects, resolution of instruments are lower. Its leads to a global uncertainty better than 2 dB at 2 sigma.

8772-45, Session PS

Polarization properties of vector solitons generated by modulation instability in circularly birefringent fibers

Evgeny A. Kuzin, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Ariel Flores Rosas, Univ. de Guanajuato (Mexico); Balder-Arturo Villagomez-Bernabe, Josue-Israel Peralta-Hernandez, Nikolai A. Korneev, Baldemar Ibarra-Escamilla, Instituto Nacional de Astrofísica, Óptica y Electrónica (Mexico); Manuel Durán-Sánchez, Univ. Tecnológica de Puebla (Mexico); Andres Gonzalez-Garcia, Instituto Tecnologico Superior de Guanajuato, (Mexico); Olivier J. Pottiez, Ctr. de Investigaciones en Óptica, A.C. (Mexico)

Principal mechanism of generation of supercontinuum is formation of solitons by Modulation Instability. Common optical fibers are randomly birefringent, and solitons formatting and traveling in them are randomly polarized. However it is desirable to have solitons with a well-defined polarization. We analyzed the two coupled propagation equations in a circularly birefringent fiber. Our equations included the soliton self frequency shift. For our best knowledge this set of equation was analyzed for the first time. We performed a transformation of

equations which reduces them to a form of perturbed Manakov task. The difference between our equations and the integrable Manakov case was considered as a perturbation. The perturbation method gives us equations for evolution of the polarization state of pulse. The evaluation equation shows that in a circularly birefringent (twisted) fiber the cross–polarization Raman term leads to unidirectional energy transfer from the slow circularly polarized component to the fast one. The magnitude of this effect is determined by the product of birefringence and amplitudes of both polarization components. Thus, solitons with any initial polarization state will eventually evolve stable circularly polarized solitons. We also made numerical analysis of two coupled nonlinear Shrödinger equations using a split-step Fourier method. The parameters of a standard fiber were used with delay between left- and right- circular polarizations of 1 ps/km that corresponds to circular birefringence in a fiber twisted by 6 turns/m. Numerical analysis confirms the analytical approximation. Moreover by numerical analysis it is possible to analyses the polarization of solitons generated by MI. We used a 30-ps, 40-W pulse with a noise imposed on them at the fiber input. Input pulses had different polarization ellipticity from circular to linear. We have found that polarization ellipticity of solitons does not coincide with the polarization of the input pulses. However it is distributed randomly around the polarization ellipticity of the input pulse. The deviation of polarization ellipticity from its value at the input is higher for linearly polarized input pulse and lower for circularly polarized input pulse. In experiment we used SMF-28 fiber twisted by 6 turns/m pumped by 1-ns pulses with wavelength tunable in the range between 1530 nm and 1550 nm. The pulses at the fiber output were separated into circularly-right and circularly-left polarization. The ratio between these pulses gives the ellipticity of the output pulses. Preliminary experimental results confirm the principal conclusions of the modeling. Our results show that circularly polarized pulses in a fiber with circular birefringence is promising for generation of supercontinuum with stable polarization.

8772-46, Session PS

Two-photon excited fluorescence with thermal light

Andreas Jechow, Univ. Potsdam (Germany) and Griffith Univ. (Australia); Henning Kurzke, Michael Seefeldt, Axel Heuer, Ralf Menzel, Univ. Potsdam (Germany)

Two-photon excited fluorescence (TPEF) is a standard technique in modern microscopy. Due to the low two-photon absorption (TPA) cross section these experiments are typically performed using pulsed laser emission at relatively high intensities. However, this can lead to photodamage of the probe. Therefore, several proposals towards an enhancement of TPA exist including the use of two entangled photons, or biphotons [1]. However, due to the lack of sufficiently bright light sources TPEF with biphotons is not established, yet.

Recently, it was proposed theoretically and shown experimentally that some striking features of biphotons can be also achieved by utilizing thermal light sources with true chaotic photon statistic. Experiments with thermal light sources are nowadays performed in a wide array of applications like ghost imaging, subwavelength lithography and metrology.

Here, we utilize truly chaotic, thermal light from a fiber-coupled super luminescence diode to demonstrate enhanced TPEF with three common fluorophores that can be used as marker molecules. We detected TPEF with powers less than 50 µW and find that the TPA rate for chaotic light is directly proportional to the measured degree of second-order coherence (DSOC), as predicted by theory.

[1] A. Jechow, A. Heuer, and R. Menzel, "High brightness, tunable biphoton source at 976 nm for quantum spectroscopy," Opt. Express 16, 13439-13449 (2008)

8772-47, Session PS

Compact blue light source by single-pass second harmonic generation of DBR tapered laser radiation

Junhee Park, Tai-Young Kang, Korea Electronics Technology Institute (Korea, Republic of); Hae-nam Hae-nam, PSI corporation (Korea, Republic of); Boobin Yim, WikiOptics (Korea, Republic of); Han-Young Lee, Korea Electronics Technology Institute (Korea, Republic of)

We demonstrated continuous-wave at 460nm on a compact visible laser module having a footprint of (75X15X12) mm. Blue light source was achieved by a single-pass second harmonic generation (SHG) in a periodically poled MgO-doped lithium niobate planar waveguide. The pump laser was a distributed Bragg reflector (DBR) tapered diode laser radiation at 920nm having a single-frequency. The diode laser consists of a 6mm long DBR tapered diode laser with a sixth order surface grating. The ridge waveguide of the tapered laser diode is 4um wide and 2mm long and consists of a 1mm long unpumped DBR section and a 1mm long pumped ridge section. The tapered section is 2mm long with a taper angle of six degree.

The output from the DBR tapered diode laser was collimated in the fast axis using aspherical lens. Due to the astigmatism of tapered diode lasers, an additional cylindrical lens was used to collimate beam in the slow axis. A half-wave plate was positioned behind the collimation lens because of the different polarization of pump source. The laser beam was focused with a cylindrical lens in the slow and fast axes, respectively which was chosen according to a simulation result in order to maximize the coupling efficiency into the waveguide facet and achieve maximal SHG conversion efficiency. The lens and crystal was fixed with UV adhesive with a 6 axis controller having a resolution of 100nm. The pump output power was 3.0W, behind the collimating, half-wave plate and focusing lens NIR power is achieved in 2.45W.

To obtain the blue light, a 300-um-wide applied for SHG. The planar waveguide was periodically poled region and crystal of 12 and 13mm long. Both waveguide facets were optically polished angle of 5.4 degree. The quasi phase-matching temperature for DBR tapered laser wavelength of 920.9nm was achieved at 20 degree and the crystal and poling period of the crystal is 4.33um at 25.5 degree. Our compact module achieved an optical conversion efficiency of 11.6% at 286mW. The power stability of the blue light was measured at output power of 268mW with a variation of 7% for a 1 hour period.

8772-48, Session PS

Frequency doubling of 1560nm laser with single-pass, double-pass and cascaded PPMgO:LN crystals and frequency locking to Rb D2 line

Junmin Wang, Shanlong Guo, Yashuai Han, Baodong Yang, Jun He, Shanxi Univ. (China)

Based on the technique of quasi-phase-matched second-harmonic generation (SHG) by using of periodically-poled PPMgO:LN crystal, three configurations of frequency doubling of continuous- wave EDFA-boosted 1560nm laser are implemented and compared for single-pass, double-pass and cascaded PPMgO:LN crystals. Our novel design of the double-pass frequency doubling configuration using one PPMgO:LN crystal has simplified the whole experimental setup and improved the frequency-doubling efficiency significantly. Also a fiber-pigtailed PPMgO:LN waveguide is utilized in single-pass configuration to achieve efficient SHG for the case of low fundamental-wave power. All these four configurations are much simpler compared with the cavity-enhanced frequency-doubling configuration in which the cavity containing SHG crystal must be actively locked to the fundamental-wave laser.

Employing the second-harmonic-wave output at 780nm and a rubidium (Rb) vapor cell, the polarization spectroscopy (PS) and the modulation transfer spectroscopy (MTS) are performed experimentally. PS and MTS of Rb D2 line are compared and employed to stabilize the 1560nm fundamental-wave laser. MTS is insensitive to the fluctuation of laser intensity and the temperature drift of atomic vapor cell, so it is a good choice for laser frequency stabilization against atomic hyperfine transition line.

8772-49, Session PS

Highly nonlinear tellurite fiber with engineered chromatic dispersion for broadband optical parametric amplification

Edmund P. Samuel, Tong H. Tuan, Koji Asano, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

In recent years several reports on parametric effects leading to broadband optical amplification shows significant solution for wavelength division multiplexing (WDM). The optical parametric amplification (OPA) offers almost noiseless amplification, under phase sensitive operating conditions. The generation of phase conjugate waves during parametric amplification has promising capability of wavelength conversion. The broadband optical parametric amplification can be achieved by using highly nonlinear fiber such has tellurite/phospho-tellurite fibers and keeping the pumping wavelength near to zero dispersion wavelengths (ZDWL). In this paper we have considered highly nonlinear fiber (HNLF) as well as pumping wavelength near to ZDW to explore high parametric gain along with broadband. These unique features of OPA are significant in optical signal processing, wavelength conversion and signal generation for WDM systems and it may lead to future optical integrated devices.

We present here the broadband and high parametric gain in highly nonlinear tellurite/phospho-tellurite optical fiber. We had successfully developed the chromatic dispersion for optical parametric amplification. The peak parametric gain obtained for 60mW pump power can be 46dB with very large bandwidth. The parametric gain have been obtained with inclusion of higher and even order dispersion parameters in phase-mismatching factor (??). It has been understood from the results that inclusion of higher order dispersion parameters the gain spectrum enhances significantly. The fourth and sixth order dispersion parameters are responsible in making possible to achieve phase-matching in normal dispersion region accounting to wavelength conversion due to nonlinear phenomenon four wave mixing. The results have been obtained for different optical fiber geometry which has resulted in chromatic dispersion, having one zero dispersion wavelength (ZDWL) and two ZDWL. It has been observed that when pump wavelength considered near zero dispersion wavelength the peak parametric gain values are almost same. While, as the pump wavelength moves away from ZDWL the sudden fall of peak parametric gain values is observed along with the decrease in bandwidth as well. The paper explores the variation in dispersion parameters, phase-matching and consecutively bandwidth of the parametric gain.

8772-50, Session PS

Second order optical nonlinear processes as tools to probe anomalies inside high confinement microcavities

Marc Collette, Normand Beaudoin, Serge Gauvin, Univ. de Moncton (Canada)

The interest toward strong electromagnetic confinement through the use of microcavities is of great interest from both the basic research and the application sides. Because generation of photons and their conversion are considered, nonlinear as well as linear optical processes are relevant. However, here we restrict our attention to nonlinear processes. From a basic point of view, electromagnetic confinement leads to the manipulation of vacuum field fluctuations. This can be formally stated by means of an anomalous commutator relating modes inside a confining cavity [M. Ueda et al, Phys. Rev. A 50, 89 (1994)]

[a1, a2†] = ?(?) ?(?2 - ?2)

This commutator differs from the canonic one due to the presence of a modulation factor, ?(?), that depends on the cavity structure. From the Schwartz inequality, it is then conjectured that such an anomalous commutation relation should lead to an anomalous uncertainty relation. However, an attempt to probe this anomaly with a beam splitter inside the cavity is theoretically proved inadequate for this task. For this reason and because they are figuring among the strongest nonlinear optical processes, our interest is currently directed toward second order nonlinear processes, namely parametric fluorescence (PF, parametric down conversion) and second harmonic generation (SHG). Indeed, likewise spontaneous emission where photon emission can be enhanced, or inhibited, it was anticipated that photon conversion mechanisms could also be strengthened, or weakened. Similarly to usual fluorescence (spontaneous emission) and making use of the anomalous commutator, it was recently showed that PF can be strongly intensified, by two orders of magnitude or more, when it occurs inside a high confinement (open) cavity. Therefore, PF could efficiently be used to probe the expected anomaly. Moreover, PF could help to scrutinize other basic concepts such as the density of states. Indeed, we emphasize that the conclusion about the intensification PF by means of confinement can be reached without resort to the concept of density of states [S. Gauvin et al, Nonlinear Optics and Quantum Optics, 43, 303-317 (2012)]. Additionally, in consideration of the simplest possible experimental scheme to probe the anomaly and because it is generally admitted that second harmonic generation (SHG) is the time reversal of degenerate parametric fluorescence, considerable attention is also devoted to SHG, because SHG experiments are much more achieved than PF ones. Actually, four theoretical models (four interaction Hamiltonians) involving various approximations where considered and the results compared with those obtained for PF. It follows that the modulation factor, ?(?), does not have the same influence on SHG as on PF, because the equations describing SHG and PF are not symmetrical regarding the influence of quantum noise. The simple formal approaches introduced as well as the results are different and complementary to those already existing [A. Aiello et al, Phys. Rev. A 58, 2446 (1998), Y. Wu et al, J. Phys. B 34, 2281 (2001)]. In conclusion, even though PF appears more sensitive to quantum noise, further SHG experiments should be nonetheless performed to fully test the realm of anomalies inside microcavities. A confirmation of the expected enhancement could introduce a supplementary way to manipulate the very basic (elementary) photon emission mechanisms and consequently opens a door toward the realization of new optoelectronic devices.

8772-52, Session PS

Experimental investigation of high power picosecond 1.06 um pulse propagation in Bragg fibers

Michal Jelínek, Václav Kubecek, Helena Jelínková, Czech Technical Univ. in Prague (Czech Republic); Vlastimil Matejec, Ivan Kasik, Ondrej Podrazky, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Different types of optical fibers have been studied for delivery of high optical powers. Silica and plastic fibers are used for the VIS and NIR spectral ranges, while sapphire, chalcogenide, hollow-core, Bragg, or photonic crystal fibers can be used also in the mid-IR range. Photonic crystal fibers have already been developed and tested for the laser radiation delivery at 1064 or 2960 nm [1,2]. Bragg fibers with silica cores and large fundamental-mode areas applicable for laser power delivery at 1064 nm have also been designed and prepared [3]. In this paper we present results of experimental investigation of high power picosecond pulse propagation in the laboratory-fabricated Bragg fibers with a silica core. The fiber consists of a silica core surrounded by three pairs of circular layers. Each pair is composed of one layer with a high and one layer with a low refractive index with a refractive-index contrast up to 0.035. For high power transmission experiments a laboratory-designed passively mode-locked quasi-continuously pumped Nd:YAG laser in bounce geometry was used as a radiation source. The laser generated 20 ps long single pulses with the energy of 10 uJ at 1.06 um [4]. Radiation transmitted through the fiber segments with different lengths was investigated from the point of view of the spatial, temporal, energetic, and spectral characteristics. The strong nonlinear effects as stimulated Raman scattering have been observed in these fibers and will be also discussed.

This research was supported by Czech Science Foundation under project no. 102/12/2361.

[1] J.D. Sheppard et al., Opt. Express 12, 717-723, 2004.

[2] A. Urich et al., Opt. Express 20, 6677-6684, 2012.

[3] M.E. Likchachev et al., Quant. Electron.36, 582-586, 2006.

[4] M. Jelínek, V. Kubecek, Laser Physics Letters 8, 657–660, 2011.

8772-53, Session PS

Pump-probe optical response of an asymmetric quantum dot molecule

Spyridon G. Kosionis, Univ. of Patras (Greece); John Boviatsis, Technological Educational Institute of Patras (Greece); Emmanuel Paspalakis, Univ. of Patras (Greece)

The nonlinear optical response of a two-level system interacting with a strong pump field and a weak probe field has been the subject of several studies for many years. The subject started 40 years ago with the seminal work of Mollow [1]. He showed that depending on the frequency and intensity of the pump field the probe field can be either absorbed, enhanced or remain intact [1]. In addition, ac-Stark shift effect is found to occur in this system [1]. Furthermore, significantly enhanced nonlinear mixing processes [2], enhanced Kerr nonlinearity with low absorption [3] and even slow light [4] can occur in this system. In the area of semiconductor quantum dots, Xu et al. [5] investigated similar phenomena in a singly charged quantum dot under a strong optical driving field by probing the system with a weak optical field and found absorption, the ac-Stark effect, and optical gain. Also, Chang and Chuang [6] demonstrated that slow light can be created in the interaction of a quantum dot with a weak probe and a strong pump field due to population oscillation.

Here, we consider an asymmetric double semiconductor quantum dot molecule [7,8] that interacts with a weak probe field and a strong pump field. The structure consists of two quantum dots with different band structures coupled by tunneling. At nanoscale interdot separation the hole states are localized in the quantum dots and the electron states are rather delocalized. With the application of an electromagnetic field an electron is excited from the valence band to the conduction band of one of the quantum dots. This electron can be transferred by tunneling to the other quantum dot. The tunneling barrier can be controlled by placing a gate electrode between the two quantum dots. In this system tunneling induced transparency and slow light have been analyzed under its interaction with a weak probe field [7,8]. We show that the application of the pump field leads to probe absorption, optical gain and the ac-Stark effect. In addition, these effects are controlled by the gate voltage.

Acknowledgements

This research has been co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: Archimedes III.

References

1. B.R. Mollow, Phys. Rev. A 5, 1522 (1972); ibid 5, 2217 (1972).

2. R.W. Boyd, M.G. Raymer, P. Narum, and D.J. Harter, Phys. Rev. A 24, 411 (1981).

3. R.S. Bennink, R.W. Boyd, C.R. Stroud, Jr., and V. Wong, Phys. Rev. A 63, 033804 (2001).

4. G.S. Agarwal and T.N. Dey, Laser Photon. Rev. 3, 287 (2009).

5. X.-D. Xu et al., Phys. Rev. Lett. 101, 227401 (2008).

6. S.-W. Chang and S.L. Chuang, Phys. Rev. B 72, 235330 (2005).

7. C.-H. Yuan and K.-D. Zhu, Appl. Phys. Lett. 89, 052115 (2006).

8. H.S. Borges et al., Phys. Rev. B 85, 115425 (2012).

8772-54, Session PS

Enhancement of optical nonlinearity of LCs with gold-nanoparticle-doped alignment layers

Hui-Chi Lin, National Formosa Univ. (Taiwan); Andy Y. G. Fuh, Ci-Yong Lin, Ming-Shian Li, National Cheng Kung Univ. (Taiwan)

In this study, the optical nonlinearity of LCs with cell substrates coated with gold-nanoparticle (AuNP) -doped PVA alignment layers were examined using the Z-scan technique. The results show that the nonlinear refractive index n2 of the sample is enhanced by the gold nanoparticles doped in the alignment layers, because of the thermal effect of the absorption by the surface of the sample through the localized surface plasmon resonance (LSPR) of the gold nanoparticles. As the concentration of AuNPs in the alignment layers of the LC sample increases, the thermal effect of the LSPR increases, and |n2| observably increases. Furthermore, the self-defocusing effect (n2<0) of the sample can be modulated by the application of an external voltage, and a self-focusing effect (n2>0) can be observed when samples are illuminated by a high-intensity laser with the application of a high voltage. Therefore, the magnitude and the sign of n2 of the sample can be modulated by combining the applied electric field and the optical field.

8772-55, Session PS

Damage thresholds of S-doped GaSe

Yurii M. Klimachev, Andrey A. Ionin, Igor O. Kinyaevskiy, Andrey A. Kotkov, Andrey Y. Kozlov, P.N. Lebedev Physical Institute (Russian Federation); Yury M. Andreev, Institute for Monitoring of Climatic and Ecological Systems (Russian Federation); Alexander E. Kokh, Konstantin A. Kokh, Trofimuk United Institute of Geology, Geophysics and Mineralogy (Russian Federation); Grigory V. Lanskii, Anna V. Shaiduko, Institute for Monitoring of Climatic and Ecological Systems (Russian Federation); Valeriy A. Svetlichnyi, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation)

High optical quality (0.1 cm-1) single crystals of pure and heavily S-doped GaSe or solid solution crystals GaSe1-xSx, x = 0.002, 0.04, 0.023, 0.090, 0.133, 0.175, 0.216, 0.256, 0.362, 0.369, 0.412, were grown by modified Bridgman method with heat field rotation. The interaction of: (a) 100 fs Ti:Sapphire laser pulses at 800 nm and (b) 2 microns, and (c) 60 ns CO2 laser pulses at 10.6 microns with the grown and low quality (observable precipitations) GaSe crystals was studied at RT. It was found: (a) up to 5-fold advantage in limit pump intensity (less than 10%-decrease in the transmission) of optimally S-doped crystals to that in pure GaSe in the first case; (b) 3-fold in the second and (c) 2-fold in the third cases, relatively. We have established that under fs pulse pump the advantages appear due to decrease in the multiphoton absorption coefficients that are depending on the spectral shift of GaSe short-wavelength transparency end with doping. Under fs pulses pump the transmission drops down to 5-10% but still reversible for all crystals. First observable damages is a result of a dissociation of sub-micrometer thick GaSe surface layer to initial elements that does not influence significantly the frequency conversion efficiency until alloying of dissociated Ga. But before multiple transient transmission effect were observed, recorded with 37 fs resolution by pump and probe method and interpreted. So, it was ascertained that sub-micrometer sized precipitations and local sliced off regions are damage centers in low quality GaSe. Multiphoton absorptions are identified as key factors responsible for the pump intensity limitation in high quality crystals. Damages observed under ns pulse pumping are caused by thermal processes with involving of nano sized precipitations. Damages related to precipitations were observed all troughs the crystal volume with specific distributions under fs and ns pumps.

8772-56, Session PS

Electronic structure of KTiOAsO4, a novel material for non-linear optical applications

Victor V. Atuchin, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation); O. Y. Khyzhun, V. L. Bekenev, A. K. Sinelnichenko, Frantsevich Institute for Problems of Materials Science (Ukraine); Ludmila I. Isaenko, S. A. Zhurkov, Institute of Mineralogy and Petrography (Russian Federation)

Potassium titanyl arsenate, KTiOAsO4 (KTA), is a representative member of KTiOPO4 (KTP) crystal family, crystallizes in a complex orthorhombic cell (space group Pna21) with the following lattice constants: a = 1.314 nm, b = 0.658 nm, and c = 1.079 nm (Z = 8) and possesses pronounced nonlinear optical properties. KTA reveals high chemical and thermal stability, appropriate birefringence, wide range

of transparency, high nonlinear optical coefficients. Additionally, KTA is considered as excellent material for applications in the infrared spectral range. In the present work we report the results of measurements of X-ray photoelectron valence-band spectra both for pristine and for Ar+ ion-bombarded (001)KTA surface. It has been established that the (001) KTA surface is very sensitive to 1.5 keV Ar+ bombardment: the long-range order of the KTA surface is lost during the irradiation, leading to the formation of completely amorphous surface layers at an ion dose of 2.1?1016 ions/cm2. In addition, the As–O bonds in KTA were found to be relatively less stable with respect to the Ar+ ion bombardment. The formation of unstable layers with chemically active and passive arsenic states observed for the (001)KTA surface is supposed to be a factor reducing the optical parameters and durability of nonlinear devices involving KTA.

To elucidate the peculiarities of electronic state occupations within the valence band region of KTA, we performed the full potential linearized augmented plane wave (FP-LAPW) band-structure calculations. Total and partial densities of states of the atoms constituting KTA were obtained. To verify the theoretical FP-LAPW data, the X-ray emission bands representing the energy distributions of some valence states of the atoms constituting KTA were recorded and compared on a common energy scale with the XPS valence-band spectrum of potassium titanyl arsenate. A good agreement of the experimental X-ray spectroscopy results and the theoretical FP-LAPW data regarding occupations of the electronic states in the valence band of KTA has been achieved.

8772-57, Session PS

Broadband laser source emitting within 2.5 - 8.3 mm

Igor O. Kinyaevskiy, Andrey A. Ionin, Yurii M. Klimachev, Andrey Y. Kozlov, Andrey A. Kotkov, P.N. Lebedev Physical Institute (Russian Federation); Yury M. Andreev, Grigory V. Lanskii, Anna V. Shaiduko, Institute for Monitoring of Climatic and Ecological Systems (Russian Federation)

Collinear cascaded laser emission frequency conversion in nonlinear crystal ZnGeP2 was realized within the 2.5 to 8.3 µm spectral range. The Q-switched multiline carbon monoxide laser (CO laser) is used in the experiments as pump. Our CO laser operated within the 5.0 - 7.5 ?m spectral range, time duration of a radiation pulse was ~1 ?s with peak power up to 4 kW. The ZnGeP2 crystal was installed at 48 degree entrance phase-matching angle. As a first frequency conversion cascade the sum frequency and second harmonic generations of CO-laser radiation within the 2.5 - 3.6 µm spectral range was obtained by ee-o type. The external and internal efficiency of this frequency conversion of fundamental lines was 1.8 % and 3.5 %, respectively. Maximum power of sum frequency radiation was near a wavelength 2.5 µm. As the second cascade a different frequency mixing this sum frequency radiation with the pump one in the same ZnGeP2 nonlinear crystal was recorded within two spectral bands from 4.3 to 5.0 µm and from 7.5 to 8.3 µm. This second cascade was possible because of different frequency generation realized at the same entrance phase-matching angle. The external and internal efficiency of frequency conversion of fundamental lines to different frequency lines within 4.3 - 4.9 µm range was 0.25 % and 0.48%, respectively. A computer simulation indicates full cover of the spectral range of 2.5 to 10 µm by this concurrent cascaded frequency conversion in one nonlinear crystal ZnGeP2 of CO-laser emission.

8772-58, Session PS

Anderson localization of light in optical lattices with PT symmetry

Dragana M. Jovic, Institute of Physics (Serbia)

There has been an increased interest in physical systems exhibit a parity-time (PT) symmetry in various fields of physics, from quantum field theory and mathematical physics [1,2], to solid state and atomic physics [3], and optics [4,5]. Convenient complex-valued potentials can be realized in optics, using the refractive index modulation that combines gain and loss regions [4,6]. This is the consequence of the equation describing the propagation of an optical beam in a medium being of the Schrödinger-equation type, with the potential proportional to the distribution of the index of refraction.

Anderson localization (AL) in disordered media [7], has been observed in a variety of classical and quantum systems [8], including light waves [9], especially in nonlinear optics and photonics, due to the emergence of new optical technologies and media, such as disordered photonic crystals and optical lattices, in which the appearance of AL considerably changes the propagation of light [9,10,11].

We have studied numerically a transverse localization of light in a uniformly disordered two-dimensional complex lattice. We have analyzed how the gain-loss component of the PT-symmetric lattice, disorder, and Kerr nonlinearity modify transverse localization of light. We aim at elucidating the effect of disorder on PT-symmetric potentials, or conversely, the effect of PT-symmetry on AL. We demonstrate enhancement of AL in PT-symmetric potential, as compared to the real-valued potential. We find that the existence of phase transition in the perfect lattice does not abruptly or qualitatively change AL. This finding stems from the fact that disorder effectively destroys PT-symmetry of the lattice, rendering the existence of the threshold strength of the imaginary component of the potential in the disorder-free lattice irrelevant. As soon as uniform disorder is introduced, PT- symmetry is lost; the eigenvalues are no longer real and there immediately appear spatially distributed gain and loss regions. We also show that there is no localization when only gain or only loss is present in the lattice, under conditions similar to the PT lattice.

REFERENCES

[1] C.M. Bender and S. Boettcher, Phys. Rev. Lett. 80, 5243 (1998).

[2] C.M. Bender, D.C. Brody, and H.F. Jones, Phys. Rev. Lett. 89 270401 (2002).

[3] N. Hatano and D.R. Nelson, Phys. Rev. Lett. 77, 570 (1996).

[4] R. El-Ganainy, K.G. Makris, D.N. Christodoulides, and Z.H. Musslimani, Opt. Lett. 32, 2632 (2007).

[5] C. E. Rüter, K. G. Makris, R. El-Ganainy, D. N. Christodoulides, M. Segev,and D. Kip, Nature Physics 6, 192, (2010).

[6] S. Klaiman, U. Günther, and N. Moiseyev, Phys. Rev. Lett. 101, 080402 (2008).

[7] P.W. Anderson, Phys. Rev. 109, 1492 (1958).

[8] P. Sheng, Scattering and Localization of Classical Waves in Random Media (World Scientific, Singapore, 1990).

[9] T. Schwartz, G. Bartal, S. Fishman, and M. Segev, Nature 446, 52 (2007).

[10] D.M. Jovi? and M.R. Beli?, Phys. Rev. A 81, 023813 (2010).

[11] D.M. Jovi?, Yu.S. Kivshar, C. Denz and M.R. Beli?, Phys. Rev. A 83, 033813 (2011).

8772-59, Session PS

Optical propagation loss measurements in electro optical host-guest waveguides

Edgars Nitiss, Martins A. Rutkis, J. Busenbergs, Univ. of Latvia (Latvia)

Optical waveguides are the key enabling elements for development of high performance and low cost nanoscale photonics devices such as switches, modulators, sensors etc. For the later waveguides with excellent nonlinear optical (NLO) and linear optical properties have to be developed. Such NLO active organic materials possess multiple advantages over the traditional inorganic materials such as low cost, easy processability, low dielectric constants and thus could be used as electro optically active components in high bandwidth EO modulators.

For the development of waveguide devices the optical quality of the waveguide is a crucial factor. One has to avoid light absorption and scattering in the core and cladding materials for best device performance. Therefore before the development of the waveguide devices the losses of the waveguides have to be estimated. For this matter a computer controlled setup for the measurement of light propagation losses in a slab or rectangular waveguides was developed. This setup was used for the estimation of propagation losses in the developed organic EO active host-guest DMABI+PMMA and DMABI+PSU waveguides. We demonstrate the influence of core

and cladding optical properties so as the EO polymer poling on the light propagation losses in the developed waveguides.

This work has been supported by the European Social Fund within the project "Support for Doctoral Studies at University of Latvia".

8772-60, Session PS

C-band amplification through fibre ring laser in generating multi wavelength

Mohd Nizam Abdullah, Sahbudin B. Shaari, Abang Annuar Ehsan, P. Susthitha Menon, Univ. Kebangsaan Malaysia (Malaysia); Mohd Nasir Zainal Abidin, Abdul Rashid Zainal Abidin, National Metrology Lab. (Malaysia)

We demonstrated multi wavelengths formation by utising a combination of fibre ring laser, three fbgs and 20 m of photonic crystal fibre with zero dispersion wavelength at 1040 nm. Although it characteristics efficiently interacts in 1040nm range lasers in efficiency of non linear effects, we determined to exploit four wave mixing (FWM) effect in generating multi wavelength at C band transmission window. Prior, the EDFA (Erbium Doped Fiber Amplifier) spectrum was performed in order to identify its performance and suitable fbgs. Two fbgs at the end of C band amplification and one at fbg at gain spectrum are selected. The fbgs assigned are FBG 1, 2 and 3 with its own specifications (1530.47 nm and reflectivity 89.9%), (1561.42 nm and reflectivity 91.6%) and (1563.95 nm and reflectivity 96.7%) respectively. Through FWM effect, new wavelengths generated successfully at gain spectrum range 1530nm to 1540nm. These findings show, multi wavelengths able to be generated even though the separation between signals which are not consistent at lengths and far among each other able to induce by sufficient energy level. The efficiency of the phenomenon is also analysed. The findings give a valuable impact and prospective relevance towards sensors and optical communications.

8772-61, Session PS

All-Optical Four-bit Toffoli gate with possible implementation in solids

Gayane Grigoryan, Vigen O. Chaltykyan, Emil A. Gazazyan, Olesya Tikhova, Institute for Physical Research (Armenia)

A universal reversible Toffoli logic gate was first introduced in 1980 [1], where it was shown that any reversible processor can be constructed using only circuits of this gate. The four-bit Toffoli gate has four inputs and four outputs. Three of the bits are control bits that are unaffected by the action of the Toffoli gate. The fourth bit is a target bit that is flipped if and only if when all three control bits are set to 1. Due to its universality the Toffoli gate is important not only in the classical calculations of conventional Boolean functions, but also in a quantum computer [3-4]. The quantum Toffoli gate recently has been successfully implemented experimentally in the ion trap [4].

In this paper we demonstrate a simple realization of all optical four- bit Toffoli gate in a resonant medium consisting of five-level atoms. The proposed scheme is based on the cyclic adiabatic population transfer resembling the techniques of STIRAP and b- STIRAP in ?-type atoms. The latter are rather well studied both theoretically and experimentally not only for individual atoms [5], but also in media [6] and have already successfully been used for designing a three-bit optical adder in the experiment [7]. In the present work we examine in detail the generalization of these population-transfer methods for five-level diagrams in order to construct a four-bit universal logic operator. The main advantage of such an operator as compared with the three-bit one is that the number of inputs and outputs is a multiple of two. We show that under certain conditions and sequence of turning on and off the laser pulses a five-level system may be reduced to an effective ?-diagram. Note that all-optical logic elements, such as implemented in experiment [7] and using coherent resonant interaction of atoms with laser pulses are necessary intermediate step in the transition from classical to quantum computations. At the same time, in order to pass directly from quantum logical schemes to classical, the latter must contain only reversible elements like the Toffoli gate [2].

1. T.Toffoli, "Reversible computing", Technical Report MIT/LCS/TM-151, Cambridge, Massachusetts, (1980).

2. M.Nielsen, I.CChuang, "Quantum Computation and Quantum Information", Cambridgee University Press, Cambridgee, UK (2000).

3. J. K. Pachos, P. L. Knight Phys. Rev. Lett. 91, 107902 (2003)

4. T. Monz, K. Kim, W. Hänsel, M. Riebe, A. S. Villar, P. Schindler, M. Chwalla, M. Hennrich, R. Blatt, Phys. Rev. Lett. 102, 040501 (2009).

5. K.Bergman, H.Theuer, B.Shore, Rev. Mod. Phys. 70, 1003 (2004).

6. G.G. Grigoryan, G. Nikoghosyan, T. Halfmann, Y.T. Pashayan-Leroy, C. Leroy, S.Guerin, Phys.Rev. A 80, 033402 (2009).

7. F.Bell, T.Halfmann, F.Remacle, R.D.Levin, Phys.Rev.A 83, 033421 (2011).

8772-62, Session PS

Structural field of K2Al2B2O7-family borate crystals

Victor V. Atuchin, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation); Bair G. Bazarov, Victoria Grossman, Baikal Institute of Nature Management (Russian Federation); Maxim S. Molokeev, Kirensky Institute of Physics (Russian Federation); Zhibzema G. Bazarova, Baikal Institute of Nature Management (Russian Federation)

Acentric borate crystals are basic materials of high-power modern nonlinear optics because of appropriate nonlinear optical coefficients, reasonable birefringence, wide transparency range including UV range and very high optical damage thresholds. The K2Al2B2O7 (KABO), space group P321, a = 8.5657(9), c = 8.463(2), discovered in ternary system K2O-Al2O3-B2O3 is a well-known nonlinear crystal applicable for frequency conversion in visible and UV spectral ranges. KABO possesses a good chemical stability, reasonable NLO properties, optical transparency in UV range up to ~ 180 nm and the birefringence as high as ?n ~ ?0.08 providing wide range lightwave phase-matching. As to KABO, a search for structural analogs was implemented in the past because the isovalent element substitution seems to be possible in potassium or aluminum sublattices. As it was found, the Al3+ ions in KABO structure can be substituted by Fe3+ ions with the formation of K2Fe2B2O7, space group P321, showing reasonable NLO properties. Regrettably, within the possible parent compounds A2Al2B2O7 (A = Na, K, Rb) the noncentrosynnetric structure is known only for KABO. The structure with a center of inversion was found for Na2Al2B2O7, space group P-31c, and, respectively, only a limited homogeneity range was obtained for solid solution K2(1-x)Na2xAl2B2O7, 0 ? x <0.6. The Rb2Al2B2O7 (RABO), space group P21/c, a = 8.901(2), b = 7. 539(1), c = 11.905(2), ? = 103.97(1) °, V = 775.3(2)?3, Z = 4 also possesses a center of inversion. Thus, it may be reasonably supposed that the isovalent substitution of Rb for K in KABO structure could result in the limited range solid solution K2(1-x)Rb2xAl2B2O7. Phase transition P321-P21/c is presumed to be at high rubidium content. Thus, the present study is aimed at the crystal chemistry analysis of all known solid solutions on the basis of KABO. As a result, a field of KABO-type structure on the a-b plane will be defined that yields the rules of cation selection for new KABO-based solid solutions.

8772-63, Session PS

Laser-induced incandescence of carbon surface: a method for temperature estimation

Katerina S. Zelenska, Sergiy E. Zelensky, National Taras Shevchenko Univ. of Kyiv (Ukraine)

A lot of optical methods have got its pursues in pyrometry to estimate temperature of incandescent objects. In previous paper [1] a new optical method was proposed for estimation of temperature of light-absorbing microparticles heated by powerful laser pulses. The method is based on some features of laser-induced incandescence (LII), notably, on the essentially non-linear response of LII to the variations of laser power. Another method for estimation of temperature of incandescent filament under vacuum was proposed in [2]. It was based on the single-wavelength measurement of thermal emission deviation

caused by the variation of heating electric current. Besides, in [3] a new optical method was proposed for estimation of temperature during cooling down of an incandescent object. The method is based on the analysis of shape of thermal emission decay curve measured at a fixed wavelength.

In the present work the investigations of thermal emission of laser-heated surfaces show that the overheated surface temperature can be estimated via single-wavelength measurements of LII with moderate variations of the initial (before the laser pulse) surface temperature. We investigated LII from the surfaces of bulk carbon samples under excitation by a Q-switched YAG-Nd3+ laser (wavelength 1064 nm, pulse duration 20 ns, laser power density 2…4 MW cm-2). The experiments show that variation of the initial surface temperature within the margins 350K+-50K (at a fixed laser power density) causes significant (twofold and more) changes of LII signals (at a fixed wavelength of 500 nm). Besides, LII signals, , demonstrate strong non-linear dependence on the laser excitation power, which can be approximated as , where depends on and takes the values 6…10. The observed features of LII of carbon surfaces, together with the results of computer simulations, gives a possibility for estimation of the maximal value of temperature reached at the surface under the irradiation by a single laser pulse. The calculations of pulsed laser heating were performed for flat surfaces using the heat transfer equation with the assumption that the material parameters (absorption coefficient, thermal conductivity, heat capacity) do not depend on the temperature and on the intensity of the laser radiation. The results of calculations are in agreement with the results of experiments. The effects of roughness of the investigated surface and of the non-uniformity of cross-beam laser power distribution on the calculated temperature field are discussed.

[1] Zelensky S.E. Laser-induced heat radiation of suspended particles: a method for temperature estimation// Journal of Optics A: Pure and Applied Optics. 1999. V.1. P.454-458.

[2] Zelensky S.E. Simple optical method for measuring the temperature of an incandescent filament under vacuum// Journal of Applied Spectroscopy. 2006. V.73, No.3. P.470-472.

[3] Zelensky S.E., Kolesnik A.S., Kopyshinsky A.V. Simple optical method for estimation of temperature using the emission decay curve// Bulletin of University of Kyiv. Series: Physics & Mathematics 2007. N.2. P.321-323.

8772-64, Session PS

Optimal doping of GaSe with isovalent elements

Victor V. Atuchin, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation); Yury M. Andreev, Institute for Monitoring of Climatic and Ecological Systems (Russian Federation); Konstantin A. Kokh, Russian Academy of Sciences (Russian Federation); Gregory V. Lanskii, Anna V. Shaiduko, Institute for Monitoring of Climatic and Ecological Systems (Russian Federation); Tatyana Izaak, Sobolev Institute of Geology and Mineralogy (Russian Federation); Valeriy A. Svetlichnyi, Tomsk State Univ. (Russian Federation)

It is well known that doping of GaSe with isovalent element can improve the efficiency of mid-IR and THz generation but it may also lead to defect generation and microstructure degradation. Nevertheless, available experimental data on optimal doping levels in GaSe are limited. Detailed information is available only for optimal Te-doping and preliminary information can be found for optimal S-doping. In present study the centimeter-size ingots of pure GaSe and GaSe crystals doped with 0.01-10 mass% of S, In, Te, Al were grown by vertical Bridgman method. The ?-polytype samples were selected for the study by developed nonlinear method. Firstly, THz absorption spectra were recorded as a function of doping level using home-made THz-TDS. GaSe crystals doped with S, In and Te shown the changes in intensity of layer rigid phonon E?(2) and E?(2) modes. The THz generation efficiency measured by optical rectification well correlates with the intensity of rigid mode E?(2). It allowed us to determine the optimally doped crystals by maximal intensity of E?(2) mode. Secondly, the Raman spectra were recorded versus dopant concentration with the help of Raman Fourier spectrometer Nicolet NXR 9650, USA. The correlation between specific features of the Raman line at 212 cm-1 and THz absorption spectra of all doped GaSe crystals was found. In particular, it is found that optimal doping in GaSe is close to a doping level that results in appearance of noticeable Davydov splitting of the Raman line at 212 cm-1 but still well below it. Davydov splitting is a result of interaction between neighbor layers in GaSe. Intensive interlayer intercalation that appears after occupation of vacancies changes the interlayer bonding forces and, respectively, Davydov splitting parameters. In such a way, the optimal doping with S is established as 2 to 3 mass%, with In as 0.5-1 mass%, with Te as 0.05 to 0.1 mass% and around 0.01-0.02 mass% with Al. So, proposed method allows identifying the optimal isovalent element doping level in GaSe by conventional Raman spectrophotometer without application of complicated and expansive THz-TDS facility.

8772-65, Session PS

Microstructure and optical properties of heterogeneous crystal GaSe:InS

Victor V. Atuchin, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation); Nina Beisel, Nikolaev Institute of Inorganic Chemistry (Russian Federation); Konstantin A. Kokh, Russian Academy of Sciences (Russian Federation); Vladimir Kruchinin, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation); Ilya Korolkov, Nikolaev Institute of Inorganic Chemistry (Russian Federation); Lev D. Pokrovsky, V. Lashkaryov Institute of Semiconductor Physics (Russian Federation); Alphiya Tsygankova, Nikolaev Institute of Inorganic Chemistry (Russian Federation); Alexander E. Kokh, Trofimuk United Institute of Geology, Geophysics and Mineralogy (Russian Federation)

Nonlinear optical crystal GaSe is a highly promising material used for frequency conversion over IR and THz spectral ranges. It is well known that GaSe is capable of incorporating different doping elements at a high content with a noticeable modification of physical properties. Up to now, many single-element dopants have been tested for incorporation into cation or anion sublattices of the GaSe crystal, and the solubility limits and real defect structure were estimated for several solid solutions. Up to now, better results have been achieved for GaSe doped with elemental S or In. The layered crystals GaSe and GaS have a similar atom arrangement in the layers and that provides a continuous set of the solid solutions GaSe1-xSx with a possible formation of several polymorph modifications defined by the layer stocking. Optical quality GaSe:In crystals are grown at a low In content. The present study is aimed at the crystal growth and complex evaluation of microstructural properties of (GaSe)1-x(InS)x crystals.

The optical quality GaSe:InS single crystal has been grown by modified Bridgman technique using nonstationary temperature distribution for effective melt mixing. The starting materials for crystal growth were Ga (6N) and Se, In, S (5N). At the first stage, polycrystalline compounds GaSe and InS were synthesized by the two zone method according to the technique described elsewhere. Then, the polycrystalline presynthesized charges were put into a quartz ampoule in molar ration GaSe:InS = 0.80:0.20. As a result, a crystal with the diameter of 7 mm and length of 100 mm was grown. The cleavage plane of the GaSe:InS crystal was found to be orthogonal to the growth direction. The phase composition of the crystal has been verified with XRD and TEM. The chemical composition variation along the crystal has been evaluated with electron probe microanalysis (EPMA), atomic-emission spectrometry with inductively coupled plasma (ICP-AES) and atomic-absorption spectrometry (AAS). The joint solubility limits in GaSe:InS system are measured as yIn = 0.28 at% and yS = 7 at%. Spectral dependencies of refractive index n(?) and extinction coefficient k(?) were determined by means of spectroscopic ellipsometry (SE).

8773-19, Session PS

Photoreadout statistics analysis during space objects image acquisition in large aperture telescope

Yury P. Shumilov, Peter A. Bakut, Vadim G. Vigon, Evgeniy A. Grishin, Victor D. Shargorodskii, Precision Systems and Instruments Corp. (Russian Federation)

The optimum restoration algorithm of images of space objects, observed through turbulent atmosphere, with due regard for photoreadout statistics on a receivers matrix is developed. On the basis of the algorithm analysis quantitative requirements to time balance of various modes of observation, admissible parameters of tool distortions, and also turbulence level of atmosphere are formulated. Laser star application efficiency in a sodium layer is analyzed during various space objects image acquisition by 3,12 m telescope. Demands for star brightness and star-forming laser characteristics are made.

Requirements also include focal unisoplanatism, time balance, isoplanatic and anticipation angles.

Possibility of results usage is analyzed when switching to an infrared waveband.

Methods of unaberrated images reception, such as method of threefold correlation and a method of extrafocal images, are compared under power and time characteristics.

8773-20, Session PS

Thermoelectric nanowire single-photon detector

Astghik A. Kuzanyan, Armen S. Kuzanyan, Institute for Physical Research (Armenia)

The current level of development of science and technology requires a new generation of devices for precise measurements. Sensors capable to detect a single photon and to determine its energy have many scientific and technological applications, including quantum computing and quantum cryptography, communications technology, homeland security, analysis of defects in microchips, space astronomy, chemical analysis, particle physics, and others.

Single-photon detectors (SPD) typically work by sensing an electrical signal that results from absorption of a photon. An ideal SPD is the one for which (1) the detection efficiency (the probability that a photon incident upon the detector is successfully detected) is 100%, (2) the dark-count rate (rate of detector output pulses in the absence of photons) is zero, and (3) the count rate is as high as possible. In addition, an ideal single-photon detector would have the ability to distinguish the number of photons in the incident pulse.

Conventional SPDs are based on photomultipliers and avalanche photodiodes and are used in a wide range of time-correlated single-photon counting applications. However, the major driver for SPD development is the rapidly expanding interest in optical quantum information applications. A revolution in photon detection is now underway thanks to advent of detectors based on superconductivity. These new tools are dramatically improving the sensitivity of measurements over the electromagnetic spectrum, from radio frequencies to visible light and gamma rays. The comparison of Superconducting Single-Photon Detectors (SSPD) with other fast photon counters available in the market shows that even not optimized SSPD is superior to other types of detectors by the sum of its technical characteristics. On the other hand, an extremely low temperature is required for the functioning of SSPD. The next problem is that the superconducting transition is often very narrow and it is very difficult to keep the temperature of the device within this range.

During the last decade the SSPD experienced a rapid development by using nanowires as a sensor. NbN superconductor nanowire detectors (with typical dimensions of ~5 nm thickness and 50–200 nm width) possess single photon sensitivity with GHz counting rate and high detection efficiency. However, very strict temperature conditions are required for their operation as well. This is why we propose a new type of a detector, namely the Thermoelectric Nanowire Single-Photon Detector (TNSPD).

We have collected and analyzed the values of thermoelectric parameters of low temperature thermoelectric materials and on this basis calculated the energy resolution and photon count rate of the TNSPD detectors. It is concluded that the TNSPD can achieve higher specifications as compared with the best SPD. The lanthanum-cerium hexaboride sensors of TNSPD are expected to reach of more than gigahertz count rates and will have a sensitivity of 0.1 eV. It means that the device is sensitive enough to register and spectrally characterize not only UV, but also optical and infrared photons, as its major competitors, the superconducting and semiconducting single-photon detectors.

8773-21, Session PS

Photon counting Lidar for deep space applications: demonstrator design

Vojtech Michalek, Michael Vacek, Ivan Prochazka, Josef Blazej, Czech Technical Univ. in Prague (Czech Republic); Marek Peca, VZLÚ, a.s. (Czech Republic)

The paper presents design of a single photon lidar device suitable for space-borne applications. The device is composed of radiation tolerant components or components that have a radiation tolerant equivalent. The design is modular so that the same core can be utilized for several photon counting applications including laser altimeter, atmospheric lidar, laser transponder or one-way laser ranging receiver. Receiver and transmitter optics can be matched to the specific application requirements, as necessary. The transmitter consists of a pulsed solid state diode pumped microchip Nd:YAG laser with second harmonic generator. It operates at a wavelength of 532 nm. Several laser versions may be employed – an externally triggered laser with repetition rate of up to 4 kHz or a free-running laser at 10 kHz. These lasers are generating pulses 350 ps and 600 ps pulses long with full-angle divergence of 8 mrad and 4 mrad respectively. The receiver is equipped with a 1 nm bandwidth optical band-pass interference filter and active quenched Single Photon Avalanche Diode (SPAD) detection module. A radiation tolerant K14 SPAD detector package developed at Czech Technical University with resolution of 20 ps r.m.s. is foreseen for space applications. Alternatively, commercial SPAD module lacking the radiation tolerance with higher detection efficiency can be used in air-borne or ground applications. The core module of the device electronics is based on a radiation tolerant FPGA. This unit is reaching a timing precision of 3 ps. The overall ranging performance of the device is as good as 5 cm resolution for ranges of several kilometers. Besides the design and construction of the device, some performance test results will be presented.

8773-22, Session PS

NbTiN superconducting nanostructures with ultrahigh critical current densities for single-photon detectors

Wojciech Slysz, Marek Guziewicz, Jaroslaw Z. Domagala, Marcin Juchniewicz, Michal Borysiewicz, Renata Kruszka, Krystyna Golaszewska, Institute of Electron Technology (Poland); Valery Kolkovsky, Institute of Physics (Poland); Jacek Ratajczak, Jan Bar, Maciej Wegrzecki, Adam Laszcz, Andrzej Czerwi?ski, Institute of Electron Technology (Poland); Roman Sobolewski, Institute of Electron Technology (Poland) and Univ. of Rochester (United States)

We present our research on fabrication and structural characterization of ultrathin superconducting NbTiN layers deposited on single-crystal Al2O3 substrates. Ultrathin NbTiN films were grown at room

temperature, using reactive RF magnetron co-sputtering from Nb and Ti targets, and were subject of the post-growth annealing process in Ar at 1000 ºC for 10 min. The thicknesses of studied NbN layers varied from 3.5 to 7 nm. We have performed extensive characterization of our films using high resolution X-ray difraction (HRXRD), atomic force microscopy (AFM), and high resolution transmission electron microscopy (HRTEM) methods. The studies exhibited fcc structure epitaxialy grown on (0001) Al2O3. The rocking curve of the (111) reflection resulted in a full width at half maximum (FWHM) of 10 arcsec, and AFM showed a smooth surface with RMS parameter below 1 nm. The HRTEM investigation proved an excellent, epitaxial quality of our nm-thick films, even in case of no thermal post-processing. HRTEM studies also demostrated that the presence of Ti did not change the lattice constant of the NbTiN crystal, as compared to the reference, pure NbN crystalline structure. The NbTiN/substrate interface was very sharp with a step-like character. Our superconducting transport measurements showed that even the thinnest, 3.5-nm-thick, films exhibited the superconducting transition temperature TC in the 10-12 K range and for thicker films, TC reached 14 K. Our ultrathin NbTiN films were characterized by ultrahigh values of superconducting critical current JC: a 4-nm-thick film tested at 5 K exhibited JC = 1.2 x 107 A/cm.2 The same 4-nm films were, subsequently, nano-patterned using electron-beam lithography. We have successfully fabricated 10 x 10 μm2 meander structures consisting of 100-nm-wide stripes. The NbTiN superconducting meanders are presently subject of optical photoresponse characterization and the results will be presented during the conference.

8773-1, Session 1

Silicon photomultipliers development at STMicroelectronics *(Invited Paper)*

Massimo C. Mazzillo, Ferenc Nagy, Delfo D. Sanfilippo, Giuseppina G. Valvo, Beatrice Carbone, Angelo Piana, Pier Giorgio G. Fallica, Salvo Coffa, STMicroelectronics (Italy)

Solid state optical detectors are considered an attractive possibility to replace standard Vacuum Photomultiplier Tubes (PMTs) in many applications, due to their higher quantum efficiency, tailored spectral response, high ruggedness and compact size, reduced sensitivity to temperature and voltage fluctuations and insensitivity to magnetic fields. More particularly, photodiodes working above their breakdown voltage in limited Geiger Mode have been demonstrated to offer outstanding possibilities in terms of high gain (>106), fast timing response with low fluctuation (<150 ps jitter) and sensitivity to extremely low photon fluxes.

The first single pixels thin junction photodiodes working in Geiger Mode were fabricated in STMicroelectronics-Catania R&D clean room facilities in early 2000. This technology was modified in 2005 when for the first time in industrial field thin trenches (1 μm wide) filled with tungsten and oxide and surrounding the active area of each pixel were integrated into Geiger-Mode Avalanche Photodiode (GMAP) arrays to prevent electro-optical cross talk effects between adjacent microcells. This GMAP technology was further modified in 2007 when the first N on P junction Silicon PhotoMultipliers (SiPMs) prototypes were fabricated. The SiPM is a large area detector consisting of a parallel array of micro-sized (20–100 ?m) GMAPs microcells with individual integrated quenching resistors. Each photodiode working as an independent photon counting microcell is connected to a common output to produce a summation device whose output signal is proportional to the number of detected photons. It is currently finding wide utilization in many applications such as medical imaging and high-energy physics due to its high gain (>106) at low operating voltage (typically a few tens of Volts), very fast timing response (<<1 ns) and excellent single photon counting capability. The main characteristics of ST SiPM technology are a low doped polysilicon quenching resistor, a thin junction depletion layer (about 1 μm) corresponding to a breakdown voltage of about 28 V, a reduced thickness (about 0.15 μm) of the quasi neutral region above the space charge region to increase the absorption efficiency in blue wavelength range and a double layer antireflection coating made of silicon dioxide (SiO2) and silicon nitride (Si3N4) optimized for blue light transmission, beyond the above mentioned structure for the optical isolation. For the use in nuclear medical imaging applications like Positron Emission Tomography (PET), a higher sensitivity in the blue region is desirable, as the emission spectra of common PET scintillators (typically Lutetium Orthosilicate (LSO) or Lutetium-Yttrium Orthosilicate (LYSO)) peak in this part of the spectrum. To this purpose P-on-N SiPMs have been recently designed and manufactured in order to exploit the higher impact ionization rate of the electrons photogenerated in quasi neutral region above the junction depletion layer to increase the avalanche triggering probability and consequently the photon detection efficiency in blue wavelength range. A low dark noise rate (≈0.8 MHz/mm2 at 5V-OV), high PDE (> 40% in P-on-N SiPMs at 5V-OV and 410 nm) and low cross talk values (≈12% at 5V-OV) sets STMicroelectronics SiPMs at the state of the art in this field.

8773-2, Session 1

Compact 32-channel time-resolved single-photon detection system *(Invited Paper)*

Andrea Cuccato, Sebastiano Antonioli, Angelo Gulinatti, Ivan Labanca, Ivan Rech, Massimo Ghioni, Politecnico di Milano (Italy)

Nowadays, many research fields like biology, chemistry, medicine and space technology rely on high sensitivity imaging instruments that allow to exploit modern measurement techniques. Among these, Time Correlated Single Photon Counting (TCSPC) has become the preferred solution when ultra-fast light signals have to be detected with extremely high time-resolution. The single-photon detector plays a key role in these advanced imaging systems, and in recent years Single Photon Avalanche Diodes (SPADs) have become a valid alternative to Photo Multiplier Tubes (PMTs), providing higher photon detection efficiency and lower power consumption. Moreover, scientific research has recently focused on single-photon detector arrays, pushed by a growing demand for multichannel systems, but a strong trade-off arises when both parallelization and high performance have to be achieved.

In this scenario, we developed a compact, stand-alone, 32-channels system for time-resolved single-photon counting applications. The system core is represented by a 32x1 SPAD array built in custom technology, featuring high time resolution (< 50 ps FWHM), high photon detection efficiency (> 45%) and low dark count rate (< 500 counts/s at -15°C). The SPAD avalanche signal is exported through an integrated inverter which is placed close to the photo detector, this way the capacitance on the sensing node is reduced. This novel structure allows to detect the avalanche event with high time-resolution while achieving negligible crosstalk between adjacent pixels. SPAD proper operation is guaranteed by a 32x1 mixed passive-active quenching circuit (AQC) array built in 0.35 μm standard CMOS technology; its digital outputs are fed to an FPGA that performs on-board processing of photon counting information, moreover data can be exported through USB interface or by a parallel 68-pin SCSI connector. On the contrary, photon timing information is directly extracted from the pixel array and converted to Current Mode Logic (CML) standard by 32 low-jitter buffers; data are exported through a custom 32-pairs parallel cable, this way the system can be easily interfaced with a multichannel TCSCP acquisition system. System has been enclosed in a compact custom aluminum case that provides a sealed chamber where SPAD array can operate in a dry nitrogen atmosphere. In order to achieve the best performance, photo-detector temperature is controlled by a feedback circuit employing a Peltier stage.

Experiments have been carried out on the developed system, resulting in a high time resolution (<50 ps FWHM) and negligible crosstalk (0.1 %) between channels.

8773-3, Session 1

Figures of merit for CMOS SPADs and arrays

Danilo Bronzi, Federica A. Villa, Simone Bellisai, Politecnico di Milano (Italy); Simone Tisa, Micro Photon Devices S.r.l. (Italy); Giancarlo Ripamonti, Alberto Tosi, Politecnico di Milano (Italy)

SPADs (Single Photon Avalanche Diodes) are emerging as most suitable photodetectors for both single-photon counting (Fluorescence Correlation Spectroscopy, Lock-in 3D Ranging) and single-photon timing (Lidar, Fluorescence Lifetime Imaging, Diffuse Optical Imaging) applications. Different CMOS implementations have been reported in literature. We present some figure of merit able to summarize the typical SPAD performances (i.e. Dark Counting Rate, Photo Detection Efficiency, afterpulsing probability, dead-time, timing jitter) and to identify a proper metric for SPAD comparison, both as single detectors and also as imaging arrays. The goal is to define a practical framework within which it is possible to rank detectors based on their performances in specific experimental conditions, for either photon-counting, photon-timing or 2D imaging applications. Furthermore we review the performances of some CMOS and custom-made SPADs, either in Silicon or in InGaAs/InP. The devices have active-area diameters varying from few micron to 500 µm. Results show that very dense CMOS SPADs can be suitable for many-pixels imagers, but SPADs with diameters up to 100 µm show the best overall optical performances (e.g. DCR < 2kcps and negligible afterpulsing) and even larger (> 100 µm-diameter) SPAD can still attain DCR < 90 kcps and can be suitable for few pixels arrays (e.g. for time-resolved spectrometers) with no need of microlenses, thanks to the high fill-factor.

8773-4, Session 1

Compact CMOS analog readout circuit for photon counting applications

Ekaterina Panina, Univ degli Studi di Trento (Italy); Lucio Pancheri, Univ. degli Studi di Trento (Italy); Leonardo Gasparini, Nicola Massari, David Stoppa, Fondazione Bruno Kessler (Italy); Gian-Franco Dalla Betta, Univ. degli Studi di Trento (Italy)

At the present time detectors providing single-photon counting resolution are attracting increasing attention in virtue of many possible applications such as 3D imaging, Positron Emission Tomography and Fluorescence Lifetime Imaging. Photomultiplier tubes and microchannel plates are still the most used detectors assuring high photon detection efficiency and high timing resolution at the same time. However, by reason of the high cost, fragility, sensitivity to external magnetic field of the aforesaid devices, Single Photon Avalanche Diode (SPAD) based devices are becoming very attractive as a perspective alternative solution. SPAD is a photodiode biased above its breakdown voltage operating in the so-called Geiger-mode. Due to the impact ionization effect into the bulk of the device, each impinging single photon may trigger a self-sustaining avalanche of up to the mA range which can be easily detected by an additional circuitry. Recently, SPADs have been assembled into arrays by means of CMOS technology. This breakthrough allowed the additional circuitry, which is necessary for SPAD quenching, data storage and signal processing, to be fabricated on the same substrate with compact size and high performance. However, a considerable shortcoming of the SPAD arrays is that they present a small fill factor. Signal processing in SPAD arrays is usually based on Time-To-Digital Converters and in-pixel digital counters for signal processing. Typically, digital implementation consists of a few hundreds of transistors thus limiting the effective photosensitive area to a few percent. Thus, the benefit of high timing resolution and wide dynamic range is worsened by low sensitivity of the array. One of the ways to decrease the electronics occupied area was found in the technology scaling. Along with this, we focus our attention on the processing circuitry revision. Our research work is aimed at the design of analog in-pixel readout for photon counting. Consisting of only a few transistors, analog circuits have shown performance comparable to the digital implementation. This approach significantly increases the pixel fill factor and, as the result, the overall array detection efficiency.

This paper presents the design and experimental characterization of a SPAD-based array with a compact analog in-pixel readout circuit for photon counting. Each pixel is composed of a SPAD, quenching circuit, window gating and analog counter. The circuit operation principle of the analog counter is based on the charge pumping, thus, the output voltage decreases proportionally to the input pulses corresponding to the SPAD ignition events. The resolution might be set by a programmable voltage step assuring a wide dynamic range. The circuit is simple and has a small area occupation, thus significantly increasing the pixel fill factor and the overall array sensitivity. The design was also targeted at low power consumption, good output linearity (both integral and differential) and high pixel-to-pixel uniformity. The paper will report on the design and experimental characterization of the array, showing that the proposed analog readout can be used for in-pixel signal processing in SPAD based image sensors.

8773-5, Session 1

Buffer direct injection readout integrated circuit design for dual band infrared focal plane array detector

Yi-Chuan Lu, Tai-Ping Sun, Hsiu-Li Shieh, National Chi Nan Univ. (Taiwan); Shiang-Feng Tang, Wen-Jen Lin, Chung-Shan Institute of Science and Technology (Taiwan)

This paper proposes dual-mode buffer direct injection (BDI) and direct injection (DI) readout circuit design. The DI readout circuit has some advantages including simple circuit, small layout size, and low power consumption. The internal resistance of photodetector will affect the photocurrent injection efficiency. We used buffer amplifier to design BDI readout circuit since it would reduce input impedance and raise injection efficiency. This paper will discuss and analyze the power consumption, injection efficiency, layout area, and circuit noise. The circuit is simulated by using TSMC 0.35um Mixed Signal 2P4M CMOS 5V process. The dimension of pixel is 30x30?m. We have design a 10x8 array for readout circuit of columns interlace. The input current setting 1nA to 10nA, when the measurement current setting 10p to 10 nA. The integration time would adjust. The circuit output swing is 2V, system noise voltage (Vrms) is 4.84mV, signal to noise ratio is 51dB, and the full chip circuit power consumption is 9.94mW.

8773-6, Session 2

Silicon photonic quantum optical devices *(Invited Paper)*

Stefan F. Preble, Rochester Institute of Technology (United States)

This talk will focus on the current state of quantum optical circuits on the Silicon Photonic platform. Topics will include our work on single photon wavelength conversion using linear adiabatic tuning of a Silicon microring resonator. It is achieved using a purely linear effect and as a result is fundamentally noiseless and has 100% conversion efficiency. We will also present results on continuously tunable optical delay devices based on coupled resonator structures and their application to single photon control. The delay device is able to realize 100's of picoseconds of delay of short (<10ps) photon pulses. We will also present theoretical models and simulations of multi-photon interactions in travelling wave resonator devices. Using this model we have predicted a highly robust resonant Hong-Ou-Mandel effect that is realized for any resonator-waveguide coupling constant and can operate over a wide range of resonance conditions. Furthermore, the transfer function approach allows for the straightforward understanding of any resonator-waveguide network with arbitrary modes. This will directly enable the application of quantum resonators to robust, scalable and efficient Linear Optical Quantum Computing gates. Lastly, we will discuss the current state of single photon sources based on four-photon scattering in Silicon waveguides and resonators. And the integration of Superconducting Nanowire single photon detectors with Silicon waveguides.

8773-7, Session 2

Photon counting delay stability as a key factor for optical time transfer

Josef Blazej, Ivan Prochazka, Jan Kodet, Czech Technical Univ. in Prague (Czech Republic)

The concept and preliminary experimental results of photon counting based two-way optical time transfer are presented. It is based on free-space optical link delimited by a pair of SPAD-based single photon detectors and small reflectors injecting optical signals into the link alternately on two injection points. Several picosecond laser versions may be employed as signal source – laser diode 43 ps at 778 nm, fiber based laser 80 ps at 531 nm or both. Expected repetition rate of experiment is 5 kHz. The NPET timing devices are used to register detection events and custom software and algorithm are used to process measured data. The long term delay stability sub-picosecond range and small temperature drifts of all elements of measuring chain are crucial to obtain useful data for final time scale comparison in picosecond range. The experimental results from measurement of long term stability of detector delays, delay independence on position in detector active area, and new achievements in quenching techniques will be presented.

8773-8, Session 2

Photon counting Lidar for deep space applications: concept and simulator

Michael Vacek, Vojtech Michalek, Josef Blazej, Ivan Prochazka, Czech Technical Univ. in Prague (Czech Republic)

The paper presents the concept and preliminary design of a single photon counting Lidar – laser altimeter – dedicated for deep space rendezvous missions towards an asteroid. The complex software simulator of the entire laser ranging and photon counting link has been developed and tested. The simulator framework is incorporating also both the three-dimensional spacecraft flight mechanics and topographical maps of the surface. Altimeter performance metrics are proposed and evaluated considering the topographical surface slope, environmental conditions, footprint coverage, and spacecraft-to-asteroid range and velocity. Overall estimated device weight and volume should not exceed 2 kg and 2 dm^2 with the power consumption below 10 W and the range evaluation precision of 5 cm. The asteroid topographical mapping and landing scenarios are discussed; specific spacecraft-to-asteroid approach phases are simulated and the range reading maximum repetition rates are determined for each operation phase. Photon counting approach enables additional functions to laser altimetry, namely the one way laser ranging and laser time transfers over interplanetary distances and absolute radiometry at the laser wavelength.

8773-9, Session 2

High accurate range finding with SPADs at 1064nm

Johann Eckl, Bundesamt für Kartographie und Geodäsie (Germany)

Single photon avalanche diodes (SPADs) provide highest detection efficiency for time of flight (ToF) measurements in the single photon regime, however the development of their output current is strongly dependent on the number of generated photoelectrons. Therefore the measured time of arrival shows some drift with changing input light level. Based on the continuity equations and the intrinsic resistance of SPADs a simple model of the avalanche breakthrough was developed to analyse this behaviour. By applying a suitable external gating circuit, e. g. by decoupling the diode from the gating capacitor, this simulation shows a slight dependency of the diodes peak output current on the number of generated photoelectrons. Experimental observations performed with a passive quenching circuit and an InGaAs/InP-SPAD showed good agreement with the simulation. In time of flight (ToF) measurements, e. g. in satellite laser ranging, this behaviour can be used for time walk compensation of the diode.

8773-10, Session 3

Photon-counting CdZnTe X-ray radiation detectors *(Invited Paper)*

Ralph B. James, Aleksey E. Bolotnikov, Giuseppe S. Camarda, Yonggang Cui, Anwar Hossain, KiHyun Kim, Utpal N. Roy, Ge Yang, Brookhaven National Lab. (United States)

Cadmium Zinc Telluride (CdZnTe or CZT) is a very attractive material for using as room-temperature semiconductor photon-counting X-ray detector because of its wide band-gap and high atomic number. In the past decade, most developments with CZT detectors focused on designing different configurations of the electrodes, mainly to minimize the effect of poor hole mobility and to improve spectroscopic and imaging performance. This approach has been very successful and a few novel detectors, such as Frisch-grid detectors and small-pixel devices, have been produced and reported. However, crystal defects in CZT materials still limit the yield of detector-grade crystals and, in general, dominate the detectors' performance. Over the past years, our research extended to characterizing CZT materials at the micro-scale level, and correlating the crystal's defects with the detector's performance. We built a set of unique tools for this research, including automated infrared (IR) transmission microscopy, X-ray micro-scale mapping using a synchrotron light source, X-ray transmission / refraction tomography, current deep level transient spectroscopy (I-DLTS), and photoluminescence measurements. In addition, we used state-of-art instruments at BNL's Center for Functional Nanomaterials (CFN) to measure some of the material's properties. Our most recent research focuses on improving crystal growth, distinguishing various crystal defects, studying the internal electrical field in CZT detectors, and clarifying the effect of thermal annealing in improving the material's properties. We will describe some of our findings in this presentation. In addition to material/device characterization, our group also conducts research on CZT-based instrument development and applications. Specifically, we developed a virtual Frisch-grid CZT detector and fabricated a hand-held gamma-ray spectrometer using this detector configuration, as well as a compact gamma camera based on pixilated CZT detectors for detecting prostate cancer. We will briefly introduce both devices in this presentation.

8773-11, Session 3

Development of position-sensitive CdZnTe detectors for imaging and spectroscopy of X- and Gamma-rays

Aleksey E. Bolotnikov, Giuseppe S. Camarda, Yonggang Cui, Gianluigi De Geronimo, Jack Fried, Anwar Hossain, Utpal N. Roy, Ge Yang, Emerson Vernon, Ralph B. James, Brookhaven National Lab. (United States)

We present the results from testing two types of sensors: 15x15x10 mm3 CdZnTe pixelated detectors and arrays of virtual Frisch-grid detectors. Both sensors employ a data acquisition system based on the H3D ASIC developed by BNL's Instrumentation Division in collaboration with the University of Michigan. Data obtained with an uncollimated 137Cs source at different conditions has helped us to reveal the details of operation principle of such devices and how their performances have been influenced by response non-uniformity and extended defects. The responses of individual sensors were correlated with several material characterization techniques.

We have tested arrays virtual Frisch-grid CdZnTe (CZT) detectors with common-cathode readout for correcting charge signals and rejection of incomplete charge collection events (ICC) are presented. The array employs parallelepiped-shaped crystals of a large geometrical aspect ratio with two planar contacts on the top and bottom surfaces (anode and cathode) and an additional shielding electrode placed on a crystal's sides to create the virtual Frisch-grid effect. The detectors are arranged in 2x2 or 3x3 detector modules with the common cathode readout by a single electronic channel. Because of the common cathode, the length of the shielding electrode can be further reduced with no adverse effects on the device performance. By implementing a novel technique for rejecting ICC events caused by the extended defects, we can achieve good spectral responses from the ordinary CZT crystals, which can be produced with higher yield and at lower cost. For such crystals, the resolution of individual detectors is expected to be in the range 0.8-1.5% with an average value of 1.3%. Arrays of virtual Frisch-grid detectors offer a robust and low-cost approach for making large-area detecting modules that can potentially substitute for more advanced, but also more expensive and less available, pixel detectors in applications with slightly relaxed requirements on position- and energy-resolution (e.g., for coded aperture telescopes). In addition, such virtual Frisch-grid arrays will require a comparably smaller number of readout channels, which allows for lower power consumption.

8773-12, Session 3

Ultra-compact 32-channel system for time-correlated single-photon counting measurements

Sebastiano Antonioli, Andrea Cuccato, Luca Miari, Ivan Labanca, Ivan Rech, Massimo Ghioni, Politecnico di Milano (Italy)

In recent years, an increasing number of applications is requiring high-performance analytical instruments capable of detecting temporal trend of weak and fast light signals. The Time-Correlated Single-Photon Counting (TCSPC) technique is currently one of the preferred solutions if picosecond timing resolution is required. Medicine, chemistry and biology are just some examples of applications in which the technique is chosen to perform such measurements.

Modern TCSPC applications require to detect both spectral and temporal fluorescence data simultaneously and from different areas of the analyzed sample, this way lowering cost and dimensions become key issues for multichannel acquisition systems. In this work we describe a new high-performance 32-channel TCSPC system designed to be used in a modern TCSPC set-up.

In the developed system the time interval measurements are performed by a 4-channel integrated Time-to-Amplitude Converter (TAC) followed by an A/D converter. The TAC array is built in 0.35 ?m Si–Ge BiCMOS technology and is characterized by extremely low crosstalk, high resolution and high conversion rate. Moreover it features a variable full scale range, from 12.5 ns to 100 ns.

The presented module is made by four fully independent 8-channel TCSPC boards each of them comprising two 4-channel TAC array. The 8-channel TCSPC board includes a 14bit 8-channel ADC to sample the TAC outputs, and an FPGA that records the measurement results and organizes the histograms. All the data, coming from the four boards, are managed by an USB HUB, included in the module, that allows real-time transmission to and from an external PC through a Hi-Speed USB 2.0 connection. Moreover the system is suitable for time-tagging measurements.

Experimental results demonstrate that the acquisition system allows high-performance TCSPC measurements, in particular: high conversion rate (5 MHz), good timing resolution (better than 30 ps FWHM with the full scale range set to 12.5 ns) and low differential non-linearity (lower than 6% of the bin width). The latter is obtained employing the dithering technique to reduce the ADC DNL.

We design the module to be very compact in order to be enclosed in a small aluminum case (160x125x30 mm).

8773-13, Session 3

The application of single photon detection technique to laser time transfer of Chinese navigation satellites

Wendong Meng, Haifeng Zhang, Zhongping Zhang, Shanghai Astronomical Observatory (China); Ivan Prochazka, Czech Technical Univ. in Prague (Czech Republic)

The first mission of Chinese Laser Time Transfer (LTT) between ground and Chinese Navigation Satellites was successfully implemented by Shanghai Astronomical Observatory of Chinese Academy of Sciences. Because of LTT payloads onboard the HEO satellites with altitude of 24,000 to 36,000 km, the single photon technology was adopted to increase the success rate of laser signal detection on satellites. The chip of detector works in Geige Mode with single photon sensitivity and the diameter of 40 um which is produced by Czech Technical University in Prague. In order to reduce the background noise in space, gate mode and two separated channels with different FOV are designed for the detector. The tests on ground show that the photo detecting sensitivity is the same as the C-SPAD detectors widely used in Satellite Laser Ranging (SLR) and the measuring precision is less than 150ps. The LTT experiments on Chinese Navigation Satellites are also present in this paper. The clock and relative frequency difference were obtained with the single shot precision of less than 300ps.

8773-14, Session 4

Superconducting single photon detectors for quantum optics *(Invited Paper)*

Valery Zwiller, Technische Univ. Delft (Netherlands)

Our group develops high performance single photon detectors based on superconducting nanowires. We develop schemes to boost the detection efficiency and implement the detectors in complete systems including optical fiber pigtailing.

8773-15, Session 4

Proximitized NbN/NiCu nanostripes as new promising superconducting single-photon detectors *(Invited Paper)*

Giampiero Pepe, Loredana Parlato, CNR-SPIN (Italy) and Univ. degli Studi di Napoli Federico II (Italy); Carmela Bonavolonta, Massimo Valentino, CNR-SPIN (Italy); Corrado de Lisio, CNR-SPIN (Italy) and Univ. degli Studi di Napoli Federico II (Italy); Roberto Cristiano, Mikkel Ejrnaes, Istituto di Cibernetica Eduardo Caianiello (Italy); Hiroaki Myoren, Saitama Univ. (Japan); Roman Sobolewski, Univ. of Rochester (United States) and Institute of Electron Technology (Poland)

We present our research on transport properties and optical response of NbN/NiCu superconductor/ferromagnet (S/F) ultrathin bilayers, patterned as either single nanostripes or series-parallel, meander-type nanostructures. The devices were operated at the temperature range far below the NbN critical temperature, down to 4.2 K. In particular, a strong enhancement of the superconducting critical current has been observed in our meander structures, due to a pinning mechanism arising from clustering of ferromagnetic atoms at the S/F interface. Moreover, our analysis of current-voltage characteristics revealed a number of voltage steps spontaneously occurring in a specific, narrow temperature range. The amplitude of these steps has been investigated as a function of temperature and their nature was explained in terms of the dynamics of phase-slip (PS) centers and PS lines spontaneously occurring in our nanostripes, acting as two-dimensional superconductors. According to a model based the time-dependent Ginzburg-Landau theory, the PS center is characterized as a nonequilibrium local state, in which normal carriers relax in energy on a characteristic time scale that reflects on the temperature dependence of PS-induced voltage steps. Thus, an analysis of such dependence sheds new light on the nature of generation of transient, localized normal regions, subsequently, leading to a better physical understanding of dark-count phenomena in superconducting single-photon detectors. Moreover, it also enables an estimation of the inelastic electron-phonon relaxation time, which in our bilayers is of the order of ~1 ps. The latter value was directly compared with 1.2±0.3 ps energy relaxation time, independently determined by us from a time-resolved optical pump-probe spectroscopy technique, typically used for investigations of nonequilibrium phenomena in superconductors. Photon counting properties on our proximitized S/F nanostripes have been investigated and compared to those of pure superconducting NbN. The photoresponse signals to ultraweak photon fluxes have been obtained by using very heavily attenuated, 400-ps-wide, 850-nm wavelength optical pulses generated by a 100-MHz repetition rate laser. Most interestingly, the falling time of the recorded voltage transients was found to be dependent on the NiCu overlayer thickness. We can conclude that, as compared to pure NbN nanostructures, our S/F, NbN/NiCu nanostripes are very promising for photon counting applications, since they are characterized by enhanced critical current densities, ultrafast energy relaxation times, and dark counts mainly limited by PS effects.

8773-16, Session 4

Integrated single photon generation and detection

Iman Esmaeil Zadeh, J. W. Niels Los, Michael E. Reimer, Gabriele Bulgarini, Technische Univ. Delft (Netherlands); Sander N. Dorenbos, Single Quantum (Netherlands); Valery Zwiller, Technische Univ. Delft (Netherlands) and Single Quantum (Netherlands)

Efficient single photon generation, manipulation and detection are the three key requirements in Linear Optic Quantum Computation (LOQC). Improvements of the efficiency of single photon emitters, of single photon detectors and linear optics integration techniques have been carried out separately. Integrating all of these three elements together remains to be done.

Here we report on the fabrication of a novel device for on chip generation and detection of single photons. Our chip uses electronically pumped InAs quantum dots embedded in InP nanowires as quantum LEDs for single photon generation at ~950nm and Superconducting Nanowire Single Photon Detector made of NbTiN meander for the detection of single photons with high efficiency.

Nanowires were transferred and connected to the electrical probes on top of the detectors with a dielectric layer in between, then their emissions were studied. The total efficiency is a function of nanowire diameter, thickness of the dielectric material and its refractive index and finally, detection efficiency of the detectors. A variation of this device comprising integrated optics components will have the potential for on chip LOQC.

8773-17, Session 4

Photoresponse studies of proximitized superconductor/ferromagnet nanostructures for photon detection

Roman Sobolewski, Institute of Electron Technology (Poland) and University of Rochester (United States); Loredana Parlato, Giampiero Pepe, Corrado De Lisio, V. Pagliarulo, Carmela Bonavolontà, CNR-SPIN (Italy); R. Arpaia, CNR-SPIN (Italy) and Chalmers University of Technology (Sweden); F. Miletto Granozio, Umberto Scotti di Uccio, CNR-SPIN (Italy); Roberto Cristiano, Mikkel Ejrnaes, Istituto di Cibernetica Eduardo Caianiello (Italy); Wojciech S?ysz, Institute of Electron Technology (Poland); Yuhan Wang, Yunus Akbas, University of Rochester (United States)

We present our research on fabrication, structural characterization, and superconducting and optical properties of ultrathin superconductor/ferromagnet (S/F) bilayers and patterned nanostripes. Our S/F structures consisted of both metallic [e.g., NbN/Ni0.6Cu0.4 (NbN/NiCu)] and oxide [e.g., YBa2Cu3O7/La0.7Sr0.3MnO3 (YBCO/LSMO)] materials. In the case of NbN/NiCu bilayers, an 8-nm-thick NbN film was sputtered first and, afterward, the samples were moved into another vacuum chamber to deposit NiCu overlayers with thicknesses ranging from 1 nm to 10-nm. All-oxide YBCO/LSMO bilayers were grown by a pulsed-laser deposition on SrTiO3 substrates in a 0.25 mbar O2 atmosphere. A 100-nm-thick YBCO base layer was deposited first and capped with either a 10-nm-thick or 35-nm-thick LSMO film. The growth process was performed at 800°C and controlled in-situ by the reflection high-energy electron diffraction method. Subsequent cooling of the samples included a prolonged exposure to 200 mbar of O2 at 500°C to promote full oxidation of YBCO through the LSMO capping. The resulting epitaxial nanostructures had excellent structural and transport properties, with ~0.3° full-width-at-half-maximum rocking curves and the sharp, 0.3-K-wide superconducting transition at 91.5 K. The bulk of our photoresponse measurements was performed using a pump-probe femtosecond optical spectroscopy technique. The pump and probe beams consisted of trains of 100-fs-wide optical pulses at 800-nm wavelength and 76-MHz repetition rate, and were generated by a self mode-locked Ti:Sapphire laser. Analysis of the recorded photoresponse signals indicated the very strong influence of the S/F interface and, overall, the transients could not be interpreted as an incoherent sum of contributions from the two individual layers. In all cases, the S/F nonequilibrium dynamics was modeled by, developed by us, a generalized, multi-temperature model. The long-term behavior was fitted with the two characteristic relaxation times. Electrical and optical investigations of successfully patterned NbN/NiCu and YBCO/LSMO stripes and meanders are presently being performed and the results will be presented during the conference.

8773-18, Session 4

NbN superconducting single-photon detector for practical applications

Alexander A. Korneev, Moscow State Pedagogical Univ. (Russian Federation)

Presently superconducting single-photon detectors (SSPD) became a mature technology with rapidly growing area of practical applications in such fields as single-photon source characterization, quantum cryptography, single molecule and ion detection.

We present our recent research into optimization of NbN SSPDs for practical applications. In particular we focused on the optimization of the detection efficiency of fibre-coupled devices for visible and infrared range. To improve the detection efficiency of the SSPD we followed approaches presented in [1, 2].

The former approach we improved by ``inverting" the light-coupling layers: first we fabricated gold mirror on the substrate then ?/4 layer of SiO and then NbN SSPD. Such a construction enabled us to avoid illumination through the substrate while coupling to single-mode fibres and thus to avoid elaborated techniques based on usage of lensed fibres and active alignment.

The latter approach was essentially the same as described in [2]: we fabricated NbN SSPD on Si wafer with ?/4 layer of SiO2 and studied spectral sensitivity of fibre-coupled devices with polarized and unpolarized light. At wavelengths of 1310 nm and 1550 nm with optimal polarization we observed detection efficiency of 44% and 35% respectively at 10 dark counts per second level. We optimized SSPD fibre-coupling for wavelength different from standard telecom, i.e. we coupled detectors to fluoride ZBLAN fibres and studied detection efficiency up to 2000 nm wavelength which is essential in study of single-photon sources beyond the spectral range of InGaAs avalanche photodiodes [3].

In visible light smaller core diameter of the fibres enabled us to reduce the device size to 5 ?m x 5 ?m thus making SSPD faster. Such devices were fabricated on SiO2 layer as well. In order to produce interference maximum in visible light we had to reduce SiO2 thickness by reactive ion etching. It is also worth noting that SiO2 layer turned out to have better surface quality compared to previously used sapphire, thus we were able not only to improve detection efficiency but also to increase the fabrication yield of good devices. SSPD coupling to lensed fibres will be presented as well.

We shall also present the results of our recent research into photon count statistics of parallelwire SSPDs in ``arm-trigger" regime. We have recently demonstrated single-photon response of such detectors with 40-nm-wide strips 10 ?m photons. Also we shall present our further research into photon-number resolving detectors as well as fabrication of the SSPD on wafers such as Si3N4 compatible with photonic waveguides and integrated photonic circuits.

[1] I. Milostnaya, et al, J. Physics: Conference Series 43 (2006) 1334–1337

[2] Tanner M. G., et al Appl. Phys. Lett. 96, 221109, (2010)

[3] D. Elvira, et al, Appl. Phys. Lett. 97, 131907 (2010)

8773-30, Session 5

Experimental boson sampling *(Invited Paper)*

Matthew A. Broome, Alessandro Fedrizzi, Saleh Rahimi-Keshari, The Univ. of Queensland (Australia); Justin Dove, Scott Aaronson, Massachusetts Institute of Technology (United States); Timothy C. Ralph, Andrew G. White, The Univ. of Queensland (Australia)

Quantum computation has attracted much attention because of the promise of new computational and scientific capabilities. The most famous quantum algorithm is Shor's factoring algorithm, which if realised will efficiently factor large composite numbers into their constituent primes, a task whose presumed difficulty is at the basis of the majority of today's public-key encryption schemes. What is not widely appreciated is that the very existence of Shor's algorithm poses a fundamental trilemma: respectively, at least one of the foundational tenets of physics, mathematics, or computer science, is untrue.

Shor's algorithm states that efficient factoring can be done on a quantum computer, which is thought to be a realistic physical device. It may be that a scalable quantum computer is not realistic, if for example quantum mechanics breaks down for large numbers of qubits. If, however a quantum computer is a realistic physical device at all scales, then the Extended Church-Turing thesis—that any computational function on a realistic physical device can be efficiently computed on a probabilistic Turing Machine—means that a classical, efficient, factoring algorithm exists. Such an algorithm, long sought-after, would enable us to break public-key cryptosystems like RSA. A third possibility is that the Extended Church-Turing thesis itself is wrong.

How do we answer this trilemma? As yet there is no evidence that quantum mechanics doesn't apply for large-scale quantum computers—that will need to be tested directly via experiment—and there is no efficient classical factoring algorithm or mathematical proof of its impossibility. This leaves examining the validity of the Extended Church-Turing thesis. One approach would be to take a task that was believed, on strong evidence, to be intractable for classical computers, and to build a physical device that performs the task efficiently. This would directly contradict the Extended Church-Turing thesis.

One such task is BosonSampling: obtaining a representative sample-distribution for n bosons scattered by some linear-optical unitary process, given by a m x m matrix, U. This task likely becomes intractable for large n, for reasons related to the fact that the amplitudes of n-boson processes are given by the permanents of n x n sub-matrices of U, and calculating the permanent is a so-called #P-complete' problem—a complexity class above even `NP-complete'. Note that BosonSampling itself is not thought to be #P-complete: the ability to solve it lets us sample random matrices most of which have large permanents, but probably does not let us estimate the permanent of a particular, given matrix. However, even for the `easier' task of BosonSampling, any fast classical algorithm would lead to drastic consequences in classical computational complexity theory, notably collapse of the `polynomial hierarchy'.

Here we test the central premise of BosonSampling in practice, experimentally verifying that the amplitudes of n=3 photon scattering events are given by the permanents of n x n sub-matrices of the unitary operator U describing the photonic quantum computer. We find the protocol to be robust, working even with the unavoidable real-world effects of photon loss, non-ideal photon sources, and imperfect photon detection. We make use of a novel method for experimental characterisation of near-unitary evolutions which is both fast and accurate.

8773-31, Session 5

Photonic hybrid multidimensional systems and their application in fundamental quantum mechanics and quantum communication

Vincenzo D'Ambrosio, Eleonora Nagali, Univ. degli Studi di Roma La Sapienza (Italy); Lorenzo Marrucci, Univ. degli Studi di Napoli Federico II (Italy); Fabio Sciarrino, Univ. degli Studi di Roma La Sapienza (Italy)

Qubits, the fundamental units of quantum information, are usually encoded by exploiting the polarization state of single photons. This choice is mainly due to the ease of manipulation of such degree of freedom as well as the reliability of the standard quantum optics techniques for single photons generation. In the last decades many efforts have been spent in the investigation of the multidimensional extension of qubit, quantum d-dimensional systems known as qudits. Indeed such resource has opened new perspectives in many fields, from fundamental quantum mechanics to quantum cryptography. Being defined in a two dimensional space, polarization is not suitable for the physical realization of qudits, however, in order to realize multidimensional quantum systems, it is possible to exploit other degrees of freedom of single photons such as path or orbital angular momentum. This last degree of freedom is defined in an infinite-dimensional Hilbert space so a qudit can be realized using orbital angular momentum alone or in combination (hybrid approach) with polarization or path. It is possible for instance to exploit q-plate technology to encode information in a four dimensional hybrid space spanned by polarization and a bidimensional orbital angular momentum subspace of a single photon (ququarts). Such states have been used for fundamental quantum mechanics investigation and quantum cryptography. The joint action of polarization and orbital angular momentum can be also exploited to realize quantum communication without a shared reference frame. We experimentally showed that , using particular hybrid states, it is possible to perform any quantum communication protocol and violate CHSH inequalities without any information about the reference frame orientation of the two parties (except the direction of propagation of the photons). Such feature could find application for instance in satellite based communication schemes.

8773-32, Session 5

Application of feed-forward in quantum phase gate and qubit state transfer

Martina Mikova, Miloslav Dusek, Miroslav Jezek, Michal Micuda, Helena Fikerova, Ivo Straka, Jaromír Fiurásek, Radim Filip, Palacky Univ. Olomouc (Czech Republic)

We have built probabilistic linear-optics programmable quantum phase gate. The gate was originally proposed by Vidal at al. and it was first time experimentally implemented in our laboratory in 2008. Now we have exploit the electronic feed-forward to increase the success probability of the gate. The application of the feed-forward doubled the success probability of the gate (we reached the theoretical limit, given by laws of quantum mechanics), however it has no negative effect on the process and output-state fidelities. The feed-forward uses the direct signal from single photon detector to modified the phase inside of interferometer.

In the second part of the contribution we introduce a directly measurable parameter quantifying a level of distinguishability of an internal states of particles carrying qubits. It determines an upper bound of the quality of the quantum state transfer. In our case we encoded information into spatial modes of light (represented by the passage of the photon through one or another path). The remaining degrees of freedom determine the internal states of particles, (frequency modes for us). We called them an environmental states. We

chose a setup where the qubit transfer is not affected by an imperfect interaction between qubits. It contains only “partial exchange” without any direct interaction. Than qubit state transfer is clearly limited only by the indistinguishability of input particles. This protocol also use the electronic feed-forward mentioned above.

Both these experiments use two correlated photons generated by spontaneous parametric down conversion and they consist of two fibre-optics Mach-Zehneder interconnected interferometers.

8773-33, Session 5

Transmitting continuous variable entangled states over long distances

Alberto Porzio, Consiglio Nazionale delle Ricerche (Italy)

Any quantum system, in interacting with the external classical environment, slowly looses its

quantumness and entanglement degrades. In a recent paper [1] we experimentally found that, even in presence of a strong decoherent transmission channel, the state generated by a sub—threshold type—II optical parametric oscillator (OPO) never disentangles, keeps breaking the quantum limit for the discord and, as resource for quantum teleportation of a coherent state, would allow, in principle, to realize quantum teleportation over an infinitely long Gaussian channel.

In this paper we extend our analysis by focusing on the behaviour of more entanglement witnesses such as logarithmic negativity and entanglement of formation. We, also, look into details to the different type of quantum properties such as EPR type correlation and Bell non-locality. Moreover, we analyse the system from the point of view of the transition from pure “un-decohered” to mixed states.

The role of an asymmetric channel or of two distinct channels for transmitting the two entangled sub-systems is evaluated and the possibility of obtaining asymmetric quantum steering effects is discussed. Eventually the discussion will focus on the experimental conditions that would take to Bell inequalities violation in a Gaussian CV entangled state produced in a sub-threshold OPO. The operational meaning of this violation is also enlightened.

The experimental data are analysed following a Kossakowski-Lindblad equation for a lossy quantum Gaussian channel and using the covariance matrix for fully describing state properties. Experimental covariance matrix are retrieved by a single homodyne detector scheme [2].

[1] D. Buono, G. Nocerino, A. Porzio and S. Solimeno, Phys. Rev. A 86, 042308 (2012).

[2] V. D’Auria, S. Fornaro, A. Porzio, S. Solimeno, S. Olivares, and M. G. A. Paris, Phys. Rev. Lett., 102, 020502 (2009).

8773-34, Session 6

An extremely low-noise heralded single-photon source without temporal post-selection

Fabrizio Piacentini, Istituto Nazionale di Ricerca Metrologica (Italy)

Single-photon sources are definitely one of the crucial elements for the rising of quantum technologies. Here we present a prototype of heralded single-photon source (at 1550 nm) not relying on temporal post-selection, obtained by implementing low-jitter detectors and fast custom electronics controlling a LiNbO_3 waveguide optical switch used as an optical shutter on the output of the source. The optical shutter is opened only for few nanoseconds in correspondence of the arrival of the heralded photons, thus heavily reducing the noise due to non-heralded photons and straylight. This source is characterized by a second-order autocorrelation function g^{(2)}(0) = 0.005(7), and an Output Noise Factor (defined as the ratio between the number of unwanted photons and the total photons at the source output channel) of 0.25(1)%.

8773-35, Session 6

Entangled photon generation on III-V semiconductor chip at room temperature

Sara Ducci, Adeline Orieux, Guillaume Boucher, Andreas Eckstein, Aristide Lemaître, Pascal G. Filloux, Christophe Manquest, Thomas Coudreau, Ivan Favero, Giuseppe Leo, Univ. Paris 7-Denis Diderot (France); Arne Keller, Univ. Paris-Sud 11 (France); Perola Milman, Univ. Paris 7-Denis Diderot (France)

The miniaturization of quantum information technologies on a chip is a field of intense research. In particular, the development of monolithic sources of entangled photons would enable the production, manipulation and detection of non-classical states of light in a single chip, thus opening the way to the realization of complex quantum operations. In this context, semiconductor materials are attracting a growing attention since they exhibit a huge potential in terms of integration of novel optoelectronic devices.

Here present two devices based on spontaneous parametric down-conversion in a semiconductor platform, AlGaAs, emitting two-photon states at room temperature and telecom wavelength.

The first one is a ridge microcavity in which a pump beam (around 775 nm), impinging on the surface of the waveguide with an incidence angle ?? generates two counterpropagating orthogonally polarized beams (around 1550 nm). Through a density matrix reconstruction we experimentally demonstrate the direct generation of polarization entangled photons with a raw fidelity of 83% to a Bell state. This is done by properly shaping the pumping beam spatial profile and without the need of any post-compensation stage to remove which-path information, which greatly simplifies the utilization of this source compared with most state-of-the-art sources. A theoretical model, taking into account the experimental parameters, provides ways to understand and control the amount of entanglement. These results open the way to the demonstration of other interesting properties of this geometry, such as the quantum state engineering in the frequency domain to obtain hyperentangled states.

The second device is a laser diode designed for photon pair generation within the laser cavity under electrical pumping. This source is based on modal phase-matching between the laser Bragg mode at 775 nm and two fundamental modes at 1550 nm guided by total internal reflection. Laser emission as well as second harmonic generation has been achieved on the same chip showing a nonlinear conversion efficiency of 35%W-1cm-2 which would lead to 10-7 pairs per pump photon for SPDC in a 2 mm-long diode.

These results show that this platform is an attractive candidate for scalable photonics-based quantum computation and quantum communications protocols.

unt the experimental parameters, provides ways to understand and control the amount of entanglement. These results open the way to the demonstration of other interesting properties of this geometry, such as the quantum state engineering in the frequency domain to obtain hyperentangled states.

The second device is a laser diode designed for photon pair generation within the laser cavity under electrical pumping. This source is based on modal phase-matching between the laser Bragg mode at 775 nm and two fundamental modes at 1550 nm guided by total internal reflection. Laser emission as well as second harmonic generation has been achieved on the same chip showing a nonlinear conversion efficiency of 35%W-1cm-2 which would lead to 10-7 pairs per pump photon for SPDC in a 2 mm-long diode.

These results show that this platform is an attractive candidate for scalable photonics-based quantum computation and quantum communications protocols.

8773-36, Session 6

High spatial entanglement via chirped quasi-phase-matched spontaneous parametric down-conversion

Jiri Svozilik, ICFO - Institut de Ciències Fotòniques (Spain); Jan

Perina Jr., Univ. Palackého V Olomouci (Czech Republic); Juan P. Torres, ICFO - Institut de Ciències Fotòniques (Spain)

By making use of the spatial shape of paired photons, parametric down-conversion allows the generation of two-photon entanglement in a multidimensional Hilbert space. How much entanglement can be generated in this way? In principle, the infinite-dimensional nature of the spatial degree of freedom renders unbounded the amount of entanglement available. However, in practice, the specific configuration used, namely its geometry, the length of the nonlinear crystal and the size of the pump beam, can severely limit the value that could be achieved. Here we show that the use of quasi-phase-matching engineering allows to increase the amount of entanglement generated, reaching values of tens of ebits of entropy of entanglement under different conditions. Our work thus opens a way to fulfill the promise of generating massive spatial entanglement under a diverse variety of circumstances, some more favorable for its experimental implementation.

8773-37, Session 6

Spatially entangled 4-photon states

Michiel J. A. de Dood, Martin P. van Exter, S. Cigdem Yorulmaz, Leiden Univ. (Netherlands)

We investigate spatial entanglement created by stimulated emission of photon pairs in a 2 mm long periodically poled KTP crystal by pumping the crystal with a picosecond pulsed pump. The use of spatial entanglement gives access to high dimensional entanglement that can be accurately resolved with relative ease by the use of a pinhole and a lens that are scanned in the far-field. Under the intense pump conditions in our experiment states with 4-photons can be generated. These states consist of either two independent pairs, or they from a true 4-photon state where all photons are produced in the same quantum state via the process of stimulated emission.

We separate the spatial correlations of these 4-photon states from the contribution due to spontaneously emitted double pairs and obtain a maximum visibility of the 4-photon state of 0.8 for a 2 mm crystal and 65 um pump waist. We investigate the details of the process by introducing a joint spatial density of the 4-photon state, which depends on the focusing conditions of the pump. From our measurements we find a universal scaling behavior of the visibility as a function of pump divergence and aperture size in the far-field. We discuss the number of Schmidt modes and the visibility as a function of the opening angle of the SPDC ring. For collinear down-conversion we find strong anti-correlations in the transverse momenta for photons produced as pairs, while stimulated emission gives perfect positive correlations in the measured joint spatial density.

8773-38, Session 6

Generation of nonclassical light by nonlinear cavities

Teppo Häyrynen, Jani Oksanen, Jukka Tulkki, Aalto Univ. School of Science and Technology (Finland)

We investigate generation of nonclassical photon states using nonlinear cavities. Nonclassical light sources and single photon emitters are essential e.g. in information processing, quantum computing and fundamental quantum optical experiments. We have recently shown that antibunched photons (i.e. nonclassical light) can be obtained from nonlinear cavities with multi-photon absorption [Häyrynen et al., Nonlinear laser cavities as nonclassical light sources, submitted (2012)]. The antibunching in nonlinear cavities occurs because the energy pumping raises the probability of states having n>0 photons but simultaneously the second order absorption in the nonlinear element causes an additional decay for states having n>1 photons relative to the single photon state. Therefore, light fields which are essentially superpositions of zero photon and one photon states are generated. These results suggest that a nonclassical light emitter could be realized by coupling a nonlinear loss element such as a two photon saturable absorber mirror [Thoen et al., Two-photon absorption in semiconductor saturable absorber mirrors, Applied Physics Letters, vol. 74, p. 3927 (1999)] or a nonlinear mirror [Schirmer et al., Nonlinear mirror based on two-photon absorption, J. Opt. Soc. Am. B, vol. 14 p. 2865 (1997)] to a light source like a light emitting diode (LED) or to a laser cavity. This type of a setup is technologically attractive since it potentially provides a room temperature realization of a photon antibunched light source with essentially standard optoelectronic materials and processing techniques. In addition to studying the maximized probability of single photon emission by optimizing the strengths of the linear and nonlinear losses, we investigate the effect of time dependent excitation of the emitter by current pulses. The optimal combination of the time dependent excitation and the antibunching provided by the nonlinear cavity is expected to significantly enhance the antibunching effects obtained purely by the nonlinear cavity and possibly provide single-photon-on-demand sources.

8773-39, Session 7

Large controllable phase shift from a single trapped ion *(Invited Paper)*

Andreas Jechow, Univ. Potsdam (Germany) and Griffith Univ. (Australia); Erik W. Streed, Benjamin G. Norton, Sylvi Haendel, David Kielpinski, Griffith Univ. (Australia)

Conventional optics such as lenses and prisms work by applying phase shifts to a light beam due to the materials refractive index. In these macroscopic devices each particle will contribute a small phase shift that will add up and impose a total phase shift of many radians. In principle, even a single isolated particle can impose a radian-level phase shift on an incoming light beam, but observing this phenomenon has proven challenging.

Laser cooled trapped atomic ions are effectively isolated atoms held at rest and largely free from perturbations, representing a quantum system with control over all degrees of freedom. Thus, they are an ideal system to test fundamental atomic and quantum physics. Recently, we have demonstrated wavelength scale imaging resolution of ytterbium ions trapped in a radio frequency Paul trap utilizing a phase Fresnel lens (PFL) [1]. This high spatial resolution and the high NA of the PFL allowed us to perform absorption imaging with a single isolated atom for the first time [2].

Here we show new results obtained with the absorption imaging technique. We have induced and measured a large optical phase shift in light scattered by a single trapped atomic ytterbium ion. The phase shift in the scattered component was unraveled by performing spatial interferometry between the scattered light and unscattered illumination light. The optical phase shift of 1.3 radians reaches the maximum value allowed by atomic theory over the accessible range of laser frequencies. Our results validate the microscopic model that underpins the macroscopic phenomenon of the refractive index.

Single-atom phase shifts of this magnitude open up new quantum information protocols, including long-range quantum phase-shift-keying cryptography and quantum nondemolition measurement.

[1] A. Jechow, E. W. Streed, B. G. Norton, M.J. Petrasiunas and D. Kielpinski, “Wavelength-Scale Imaging of Trapped Ions using a Phase Fresnel lens,” Optics Letters 36, 1371 (2011)

[2] E.W. Streed, A. Jechow, B.G. Norton, and D. Kielpinski “Absorption imaging of a single atom, “ Nature Communications 3, 933 (2012)

8773-41, Session 7

Overcoming decoherence in the collapse and revival of spin Schrödinger cats

Mark J. Everitt, Loughborough Univ. (United Kingdom); William J. Munro, NTT Basic Research Labs. (Japan); T. P. Spiller, Univ. of Leeds (United Kingdom)

In addition to being a very interesting quantum phenomenon, Schrödinger-cat state swapping has the potential for application in the preparation of quantum states that could be used in metrology and other quantum process- ing. We study in detail the effects of field decoherence on a Schro ?dinger-cat state-swapping system comprising a set of identical qubits, or spins, all coupled to a field mode. We demonstrate that increasing the number of spins actually mitigates the effects of field decoherence on the collapse

and revival of a spin Schro ?dinger-cat state, which could be of significant utility in quantum metrology and other quantum processing. (arxiv:1101.1420v2)

8773-42, Session 7

Matched propagation of Raman-resonant frequency chirped pulses

Nora K. Vecseine Sandor, Gagik P. Djotyan, Wigner Research Ctr. for Physics of the H.A.S. (Hungary)

Adiabatic control (AC) of atoms by laser fields is an important field of recent quantum optics and allows various applications such as high harmonic generation, multiphoton ionization, nonlinear frequency conversion, and several transparency effects.

The main idea of AC is adiabatically tuning one of the parameters of the atom-laser interaction in order to drive the atomic state along an adiabatic path in the system. Interaction schemes based on AC are widely applied, since they allow robust control of the atomic populations and coherences, therefore important tasks such as creation of coherent superpositions among certain atomic states or population transfer among ground states without excitation can be easily achieved. Among other important techniques, one way to realize AC is using coupling laser-fields with small monotonous frequency-modulation (frequency chirped pulses).

The field of transparent propagation effects is closely to related to AC, because the lossless propagation is usually based on an adiabatic population trapping mechanism. In this way, atomic excitation, which would cause losses in the coupling laser fields, is avoided. Such effects have been shown for laser pulse pairs having constant frequency in several arrangements: electromagnetically induced transparency (EIT), matched pulse propagation, adiabatons; and for a single frequency-chirped laser pulse. In view of these phenomena the question naturally arises if there is a transparency effect for frequency chirped laser pulse pairs, as well.

In this communication, propa gation of classical fields is analyzed in an optically thick medium of cold atomic gas. The atom-field interaction is described in a semiclassical way: the dynamics of the atoms is given by the quantum mechanical master-equation, while the back-action of the atoms on the laser fields is treated by the classical Maxwell equation.

The medium is modeled by an ensemble of noninteracting, identical atoms having a lambda-structure as working levels (one excited state and two ground states), initially prepared in one of the ground states. Both of the atomic transitions are separately driven by quasi-resonant laser fields, frequency chirped in the same way around the corresponding atomic transition frequency.

If the above described pair of chirped laser pulses interacted with an optically thin medium or a single atom, they would induce such an adiabatic transition among the working levels that results in a strong excitation of the atom(s).

However, in the optically thick medium, the atoms are only excited at the boundary of the medium. We show that after a relatively short transient, the frequency-chirped pulse pair is affected by the atoms in such a way that instead of exciting the atoms, they create a certain coherent superposition of the ground states (tunable by the parameters of the incoming fields), and they propagate in the remainder of the medium without significant further losses.

This quasi-transparent propagation effect of the Raman resonant frequency chirped pulse is not only interesting in the point of view of the laser fields, but the on-demand creation of coherent superpositions among the atomic states along the optically thick medium may find applications in quantum optical experiments and quantum informatics.

8773-43, Session 7

Two-atom system as a directional frequency filter

Vassilis E. Lembessis, Omar M. Aldossary, King Saud Univ. (Saudi Arabia); Zbigniew Ficek, King Abdulaziz City for Science and Technology (Saudi Arabia)

In a recent experiment Shegai et al. [1] have shown that a bimetallic particle dimer composed of gold and silver atoms may work as a directional frequency filter which scatters light of different frequencies in different directions. A phase difference between emitters required for the directional scattering of light was determined by the complex particle polarizabilities and therefore varies with the size, shape and material composition of the particles in accordance with their plasmon resonance characteristics.

In this presentation, we give a theoretical explanation of the experimental results in terms of interference between light fields emitted by nonidentical radiators. We also show that this scheme could work as a light nano-antenna for directional scattering. We assume that the radiators are represented by two non-identical closely spaced photonic nanostructures or atoms modelled as two-level systems of transition frequencies ?1 and ?2, located along the x axis at points x1 = ?a/2 and x2 = a/2, distant a from each other. We assume that the atomic transitions are damped with rates ?1 and ?2, respectively, and ignore any direct interaction between the atoms [2]. The atoms are driven by a weak laser field of the Rabi frequency ? ? ?1,?2, propagating along the z direction and polarized in the y direction. The frequency of the laser field ?L is detuned from the atomic transition frequencies by ∆1 = ?1 ? ?L and ∆2 = ?2 ? ?L , respectively. Thus, the nanostructures can be distinguished by unequal detunings and/or unequal damping rates.

We calculate the intensity I(x,z) of the superposed light scattered by the atoms and detected by a single detector at an arbitrary point on the (x, z) plane, and find

I(x,z) = I1(x,z)+I2(x,z)+Iint(x,z), (1)

where I1(x,z) and I2(x,z) are the intensities of light scattered by the individual atoms, and the interference term is of the form

Iint(x,z) = Dsin(?L [p+(x,z)? p?(x,z)]), (2)

in which D = |?|2(∆2?1 ?∆1?2) and p±(x,z) = (x±a/2)2 +z2. We see that the intensity exhibits a sine modulation with the separation p+ (x, z) ? p? (x, z) of the two passes from the atoms and with the amplitude of the modulation D. The modulation reflects the presence of a constant phase relation between the atoms induced by the driving field, which could lead to a directional emission of the scattered light.

Consider two cases. In the first, we assume that the atoms have equal damping rates, ?1 = ?2 ? ?. One can easily notice from Eq. (2) that in this case the amplitude of the interference term becomes independent of the frequency of the driving field, i.e. the amplitude can be written as D = |?|2 ∆?, where ∆ = ?1 ? ?2 is a detuning between transition frequencies of the atoms. It is interesting that the sign of the interference term depends solely on the difference between the atomic transition frequencies. Consequently, the constructive interference, I(x,z) > I1(x,z) + I2(x,z), occurs for ?2 > ?1. In other words, independent of the laser frequency the scattered light is turned towards the atom of larger transition frequency. In the second case, we assume that ?1 differs from ?2. In this case, the sign of the amplitude D, and consequently the direction of the scattered light can be controlled by the laser frequency. In particular, when ?1 =?2 ??0, i.e. ∆1 =∆2 ?∆L =?0??L, the amplitude D reverses sign once we move from either ?1 >?2 to ?1 < ?2 or from ∆L < 0 to ∆L > 0. Thus, for a given relation +between ?1 and ?2 and a position of the detector on the positive side of the x axis, the scattered light can be turned either towards the atom 1 or the atom 2. For instance, provided that ?1 > ?2, the scattered light turns towards the atom 1 when ?L > ?0, but turns in the opposite direction, towards the atom 2, when ?L < ?0. This clearly illustrates that the system may work as a light nano-antenna for directional scattering.

References

[1] T. Shegai, S. Chen, V. D. Miljkovic, G. Zengin, P. Johansson, and M. Ka ?ll, Nature Commun. DOI:10.1038/ncomms1490 (2011).

[2] Z. Ficek and R. Tanas, Phys. Rep. 329, 369 (2002).

8773-44, Session 7

Measurement of hyperfine splitting and determination of hyperfine structure constant of Cs 8S_1/2 state by using of ladder-type EIT in Cs vapor cell

Junmin Wang, Jie Wang, Huifeng Liu, Baodong Yang, Jun He, Shanxi Univ. (China)

Based on a ladder-type cesium (Cs) atomic system consists of the 6S_1/2 ground state, the 6P_1/2 intermediate state and the 8S_1/2 excited state, a 761nm coupling beam and a 894nm probe beam counter-propagating in a Cs vapor cell yields the two-photon Doppler-free configuration and allows us to observe narrow electromagnetically-induced transparency (EIT) resonances with low-power diode lasers.

Using a novel scanning mode for the ladder-type EIT in which the 761nm DFB coupling laser is scanned and the 894nm DBR probe laser is frequency locked, multiple EIT signals without background are achieved and employed to measure the hyperfine splitting of Cs 8S_1/2 state (between F"=3 and F"=4 hyperfine levels). A fiber-pigtailed wave-guide-type phase modulator and a temperature-stabilized Fabry-Perot cavity are used to provide a precise frequency marker.

Furthermore, the hyperfine structure constant of Cs 8S_1/2 state (here it is the hyperfine magnetic dipole constant, A) is determined based on the measured hyperfine splitting. The impact of the external magnetic field on the measured hyperfine splitting of Cs 8S_1/2 state is also analyzed and investigated.

8773-46, Session 7

Noiseless amplification of weak coherent fields without external energy

Mikko P. J. Partanen, Teppo Häyrynen, Jani Oksanen, Jukka Tulkki, Aalto Univ. School of Science and Technology (Finland)

Amplification of a pure state by any linear deterministic amplifier always introduces noise in the signal and results in a mixed output state. However, it has recently been shown that noiseless amplification becomes possible if the requirement of a deterministic operation is relaxed. Usually, nondeterministic amplifiers rely on using single photon sources. In contrast, we propose a noiseless amplification scheme where the energy required to amplify the signal originates from the stochastic fluctuations in the initial field itself.

The proposed scheme consists of devices that are generally used in quantum optical experiments i.e. beam splitters, photodetectors, and a quantum nondemolition (QND) measurement apparatus. A QND measurement utilizes the energy fluctuations of the initial field to replace the single photon source that would otherwise be needed as in the scheme suggested by Zavatta et al. [Nature Photonics, vol. 5, pp. 52-56, 2011]. The operation of our proposed amplifier is shortly described as follows: first a single photon is subtracted from the initial field by a beam splitter and it is verified using a QND measurement apparatus. Second, the subtracted photon is added back to the field by a beam splitter and a photodetector. Finally, another photon is subtracted from the field using a beam splitter and a conventional photodetector. The resulting output field is an amplified coherent field with high fidelity.

We apply the Wigner function formalism to analyze our noiseless amplification scheme and to investigate the relation between the amplification and its success rate as well as the statistics of the output states after successful and failed amplification processes. Furthermore, we also optimize the setup to find the maximum success rates in terms of the reflectivities of the beam splitters used in the setup and discuss the relation of our setup with the previously reported setups. In addition, the states after failed amplification are examined and the possibility of repeated amplification process is discussed.

8773-45, Session PS

Influence of hydrostatic pressure on electronic states and optical properties of spherical quantum dots

Hovhannes K. H. Tevosyan, Russian-Armenian State Univ. (Armenia); David B. Hayrapetyan, Russian-Armenian State Univ. (Armenia) and State Engineering Univ. of Armenia (Armenia); Eduard M. Kazaryan, Russian-Armenian State Univ. (Armenia)

In this paper the direct interband light absorption in spherical quantum dot with modified Pöschel-Teller potential made of GaAs under influence of hydrostatic pressure are studied. We will use the effective mass approximation method for obtaining the energy spectrum and wave functions of charge carrier in spherical qunatum dot. For the regime of strong size quantization analytic expressions for the particle energy spectrum, absorption coefficient and dependencies of effective threshold frequencies of absorption on the geometrical sizes of quantum dot are obtained. We will consider only the strong size quantization regime, when the Coulomb interaction between electron and hole can be neglected. Furthermore, we will consider the case of a heavy hole, when the effective mass of hole much more the effective mass of electron. The selection rules corresponding to different transitions between quantum levels are found. Hydrostatic pressure is a thermodynamic variable for the solid state, which provides a powerful tool to control and investigate the electronic, excitonic, impurity states and optical properties of semiconductor materials. Pressure increases the direct gap in semiconductor materials and modifies the electron and hole effective masses. So influence of hydrostatic pressure will change the optical properties and energy spectrum of charge carriers in quantum dots.

8773-47, Session PS

The simple theoretical analysis of quantum well wires superlattice (QWSL) of communication technology

Subhamoy Singha Roy, JIS College of Engineering (India)

The basic qualitative features of the field-emitted power from QWSL would be unchanged in the presence of the said effects. The theoretical results as given here would be useful and can also be used as a technique for proving the band structure of the QWSL. Finally, it may be noted that the basic aim of this chapter is not only to formulate the expression of the field emitted power from the quantum wire SL and the constituting materials but also to develop the expression of no since the study of the electron transport and formulations of the various transport co-efficient of quantum effect devices are directly based on the temperature dependent carrier statistics in such quantized materials

8773-48, Session PS

Coherent cooling of atoms in a frequency-modulated standing laser wave

V. Yu Argonov, V.I. Il'ichev Pacific Oceanological Institute (Russian Federation)

We propose a novel method of coherent laser cooling of atoms in a standing light wave. The wave function of a moderately cold atom in a stationary near-resonant standing light wave delocalizes very fast due to wave packet splitting. However, we show that frequency modulation of the field may suppress packet splitting for some atoms having specific velocities in a narrow range. These atoms remain localized in a small space for a long time. We propose that in a real experiment with cold atomic gas this effect may decrease the velocity distribution of atoms (the field traps the atoms with such specific velocities while all other atoms leave the field). In this study, the reported effect is analyzed both theoretically (semiclassical model) and numerically (purely quantum model). We simulate quantum evolution of particular cold atomic wave packets (both trapped and not trapped) and provide general analytical estimations of trapping conditions.

8774-1, Session 1

Two-dimensional hybrid metallo-dielectric nanostructures directly realized on the tip of optical fibers for sensing applications

Alessio Crescitelli, Armando Ricciardi, Marco Consales, Univ. degli Studi del Sannio (Italy); Emanuela Esposito, Istituto di Cibernetica Eduardo Caianiello (Italy); Antonello Cutolo, Andrea Cusano, Univ. degli Studi del Sannio (Italy)

The “Lab-on-Fiber” concept envisages the integration of highly functionalized micro and nano-scale materials within a single optical fiber, aimed at the development of a new generation of miniaturized and advanced “all-in-fiber” technological platforms (the “labs”) for both communication and sensing applications. The Lab-on-Fiber Technology would thus represent the basis of a technological revolution in the photonic world, enabling the implementation of fiber-based multifunction sensing and actuating systems with unique advantages in terms of miniaturization, light weight, cost effectiveness, robustness, power consumption and information control. Multifunctional labs integrated into a single optical fiber, exchanging information and fusing sensorial data, could provide effective auto-diagnostic features as well as new photonic and electro-optic functionalities useful in many strategic sectors such as optical processing, environment, life science, safety and security. The lab design involves the exploitation of all those phenomena enabling light manipulation and control such as trapping and guiding effects in photonic crystals and quasicrystals along with plasmonic nanostructures, eventually combined all together in hybrid metallo-dielectric devices. However, the realization of highly integrated optical fiber devices requires that several nano-sized structures be fabricated, embedded and connected all together for achieving the necessary light-matter interaction and physical connection. Therefore, a key aspect for the implementation of such a novel technology consists on the definition of valuable fabrication methodologies able to integrate and process, at micro and nano-scale, several materials with the desired physical, mechanical, magnetic, chemical and biological properties onto optical fibers.

In this contribution we introduce a reliable fabrication process enabling the integration of dielectric and metallic nanostructures directly on the tip of optical fibers. It involves conventional deposition and nanopatterning techniques typically used for planar devices, but here adapted to directly operate on the fiber facet. Following this approach, with a view towards possible applications, we also demonstrate a first technological platform based on the integration, onto the optical fiber tip, of two-dimensional hybrid metallo-dielectric nanostructures supporting localized surface plasmon resonances, that can be efficiently used for label free chemical and biological sensing and as a microphone for acoustic wave detection. Overall, our results evidence how the definition of viable lab-on-fiber technologies would enable the realization of technological platforms completely integrated in a single optical fiber, for exploitation in many application fields.

8774-2, Session 1

Remote distributed optical fibre dose measuring of high gamma-irradiation with highly sensitive Al- and P-doped fibres

Alexey V. Faustov, SCK CEN (Belgium) and Univ. de Mons (Belgium) and St. Petersburg State Polytechnical Univ. (Russian Federation); Andrei Gussarov, SCK CEN (Belgium); Marc Wuilpart, Univ. de Mons (Belgium); Andrei A. Fotiadi, Univ. de Mons (Belgium) and Ioffe Physico-Technical Institute (Russian Federation) and Ulyanovsk State Univ. (Russian Federation); Leonid B. Liokumovich, St. Petersburg State Polytechnical Univ. (Russian Federation); Igor O. Zolotovsky, Ulyanovsk State Univ. (Russian Federation); Alexandr L. Tomashuk, Fiber Optics Research Ctr. (Russian Federation) and Ulyanovsk State Univ. (Russian Federation); T. de Schoutheete, Laborelec (Belgium); Patrice Mégret, Univ. de Mons (Belgium)

We present our results on measuring distributed Radiation-Induced Attenuation (RIA) by means of a commercially available Optical Frequency Domain Reflectometry (OFDR) system. We chose four different highly gamma-radiation sensitive fibres, two of which were doped with Al and two with P. The dose rate during irradiation was about 560Gy/h. The irradiation were conducted at two temperatures of 30°C and 80°C. The irradiation at different temperature were needed for taking into account temperature dependence of the annealing speed of RIA. The RIA measurements were taken by means of two techniques. First one consisted in the spatially integrated spectral transmission detection using an Optical Spectra Analyser (OSA) and the second was based on distributed RIA measuring by means of the OFDR. All four fibres demonstrated a high saturation-like increase of RIA with the dose up to several tens of decibels per meter detected by OSA. In case of OFDR measurements the change of the attenuation in an optical fibre resulted in a change of the slope of the corresponding Rayleigh backscattering trace which was clearly observed during the experiments. The RIA dependences measured with the OFDR were in a reasonable agreement with the measurements obtained with OSA. This allows us to use the dependences of RIA on absorption dose obtained by means of OSA for the distributed dose measuring based on the OFDR technique. We also irradiated different lengths of one of the P-doped fibers to see if it influences accuracy of the distributed dose detection. The results of the presented experiments are noteworthy since they are considered to be a basis for a dose estimation model based on RIA in which temperature oscillations are taken into account.

8774-3, Session 1

Nanoliter-scale, regenerable ion sensor: sensing with surface functionalized microstructured optical fiber

Sabrina Heng, Mai-Chi Nguyen, Roman Kostecki, Tanya M. Monro, Andrew D. Abell, The Univ. of Adelaide (Australia)

The ubiquitous nature of metal ions in the environment and biology presents a real need to develop new methodology for their rapid and efficient detection. Such sensors would have applications in disease diagnosis and study, as well as environmental sensing. In an effort to meet this need, we have developed the first nanoliter-scale, regenerable ion sensor based on microstructured optical fiber (MOF). The air holes of the MOF were functionalized with a monoazacrown bearing spiropyran to give a photo-switchable sensor that detects lithium ions down to 100nM in nanoliter-scale volumes. We have demonstrated that ion binding is turned on and off on upon irradiation with light, with the sensor being unaffected by multiple rounds of photoswitching. More importantly, we have showed that unbound ions are flushed from the fiber in the ‘off’ state to allow the sensor to be reused. The integration of an ionophore into the sensor paves the way for the development of highly specific light-based sensing platforms that are readily adaptable to sense a particular ion simply by altering the ionophore design. This work presents advances in both fiber sensing technology and in developing fast, sensitive “point of care” ion sensing methods that can be easily deployed, are disposable and affordable, particularly in the areas of disease diagnosis. Ongoing work is concerned with designing novel ionophores for binding specific ions and decreasing the detection limit of the sensor, with the aim of sensing down to the pM levels as recently demonstrated by our group where the detection of CdSe quantum dots down to 10 pM levels has been demonstrated.

8774-4, Session 1

Influence of the lamination process on the plastic optical fiber sensors embedded in composite materials

Piotr Lesiak, Mateusz Szelag, Michal Kuczkowski, Stefan Awietjan, Slawomir Ertman, Daniel Budaszewski, Andrzej W. Domanski, Tomasz R. Wolinski, Warsaw Univ. of Technology (Poland)

Composite materials are a high strength and low weight alternative to the use of traditional metallic alloys parts. Aeronautics manufacturers have clearly indicated the trend toward greater use of composite materials in aircraft. Composite materials offer significant economic and environmental advantages and a significant volume of research all over the world is carried out by manufacturers to provide access to low-priced but quality reliable products. With the growing use of high performance composite materials in critical structures, it has become increasingly important for 'smart' systems to monitor these materials. Using polarimetric fiber sensors embedded into the weave structure of carbon fiber epoxy composites offers the capability to monitor these composites during manufacture, cure, general aging, and damage. Plastic optic fiber sensors (POFS) technology allows greater insight into damage progression and can be used to validate numerical models. Fatigue damage assessment techniques capable of rapidly and accurately locating danger areas in composites are needed for commercial and industrial applications. Such 'smart' composite structures meet the criteria for knowledge-based economic development and innovation in Europe and furthermore have a potential to reduce accidents and thus serve to improve the safety and quality of life of European citizens.

In recent years, many experiments and researches have been carried out on laminated composites to obtain optimal mechanical properties, but the influence of the lamination process on strain distribution in the composite material is very important too. Measurements made for the different HB fiber sensors built-in composite materials show that strain sensitivities are different in the HB sensors after the lamination process in comparison to the original values without lamination. These experiments suggest that the type of the fiber coating layer can be responsible for behavior of the fiber inside the composite material.

Composite structures are made from two or more constituent materials with significantly different physical or chemical properties and they remain separate and distinct in a macroscopic level within the finished structure. This feature allows for introducing an optical fiber sensors matrix into the composite material. In this paper we present that interactions between composite material and optical fibers during manufacturing process are very significant. Lamination process can dramatically change strain sensitivity of the highly birefringent (HB) fibers.

Silica-based HB fibers have severe limitations due to their coating layers while embedded into the composite: a hard coating layer easily transmitts radial stress to the sensing fiber and changes its birefringence. Two coating layers – hard and soft – attached to the HB fiber do not influence fiber birefringence since the second (soft) layer can easily absorb any lateral force. On the other hand, a soft coating does not provide any proper transmission of the longitudinal strain. Hence, soft polymer materials used in manufacturing process of the POFs can solve this limitation.

8774-5, Session 1

Inscription of first order Fiber Bragg Gratings in sapphire fibers by 400 nm femtosecond laser pulses

Tino Elsmann, Tobias Habisreuther, Albrecht Graf, Manfred Rothhardt, Hartmut Bartelt, Institut für Photonische Technologien e.V. (Germany)

Fiber Bragg gratings (FBG) are suitable for measurements in harsh environments, because they are inert to electromagnetic radiation, very small, robust and embeddable into different compound materials. But for high temperature regimes, especially for temperatures beyond 1000 °C conventional fibers made of silica cannot be used due to their lower softening point.

For such high temperatures FBGs in sapphire are of great interest, since the crystalline sapphire material is stable for temperatures beyond 2000 °C. Sapphire has a very high refractive index of about 1.74, so that the grating period of the FGB has to be very small in the order of 440 nm for a reflection wavelength in the standard telecommunication C-band (1530-1565 nm). With the common inscription wavelength of 800 nm, this is not possible and until now the only gratings reported are of higher orders. For our inscription we used a frequency doubled Ti:Sa amplified laser system, which provides femtosecond laser pulses with a sufficiently short wavelength of 400 nm for first order FBGs. The inscription itself was done using a tunable, phase mask based, two beam interferometer. With the interferometer the grating period can be tuned easily by rotating the interferometer mirrors, and multiplexing becomes applicable with only one beam splitting phase mask in the interferometer. Multiplexed gratings have been realized and their temperature dependency up to more than 1000 °C was characterized in a furnace by evaluating their reflection spectra. The sapphire fibers used were realized by air clad monocrystalline sapphire rods of 100 µm diameter guiding several hundreds of modes. This makes a multimode interrogation concept necessary, which will also be presented.

8774-6, Session 1

Spectral-domain measurement of polarimetric sensitivity of a side-hole fiber to temperature and hydrostatic pressure

Petr Hlubina, Technical Univ. of Ostrava (Czech Republic); Jacek M. Olszewski, Tadeusz Martynkien, Wroclaw Univ. of Technology (Poland); Pawel Mergo, Univ. Marii Curie-Sklodowskiej (Poland); Waclaw Urbanczyk, Wroclaw Univ. of Technology (Poland)

In this paper, we present a spectral interferometric technique [1] for measuring the spectral polarimetric sensitivity of a birefringent side-hole fiber to temperature and pressure. We used a simple experimental setup comprising a broadband source, a polarizer, a birefringent fiber under test, a birefringent delay line, an analyzer and a compact spectrometer. The spectral interferograms, characterized by the equalization wavelength at which spectral interference fringes have the highest visibility (the largest period) due to the zero overall group birefringence, were processed by a new method [2] to retrieve the phase as a function of the wavelength. First, from the retrieved phase functions corresponding to different temperatures of the fiber under test, the spectral polarimetric sensitivity to temperature was obtained. Second, from the retrieved phase functions corresponding to different pressures in a chamber with the fiber under test, the spectral polarimetric sensitivity to pressure was obtained. The spectral dependence of polarimetric sensitivity to pressure was also compared with that obtained from a shift of the spectral interferograms not including the equalization wavelength, and good agreement was confirmed.

[1] P. Hlubina, et al., Sensors, 12, 12070-12081 (2012).

[2] P. Hlubina, J. Olszewski, Opt. Commun., 285, 4733-4738 (2012).

8774-7, Session 1

Multianalyte detection using fiber optic particle plasmon resonance sensor based on plasmonic light scattering interrogation

Hsing-Ying Lin, Chen-Han Huang, National Cheng Kung Univ. (Taiwan); Lai-Kwan Chau, National Chung Cheng Univ. (Taiwan)

The resonance frequency of localized surface plasmon resonance (LSPR), also known as particle plasmon resonance (PPR), of metal nanoparticles has been shown to be strongly dependent on the particle's size, shape, composition, and the dielectric properties of surrounding medium. The PPR excitation of metal nanoparticles can result in wavelength-selective absorption with extremely large molar extinction coefficients of 3.5x10^8 M^?1cm^?1 and resonant Rayleigh scattering with an efficiency equivalent to that of 3x10^5 fluorophores. For a gold or silver particle, as the surrounding medium refractive index increases, the Rayleigh and Mie equations show that the light scattering intensity of a particle increases continuously, and the color of the scattered light red shifts. Moreover, due to plasmonic effects, the scattering from a metal nanoparticle is relatively intense and much higher than that of a polystyrene nanobead of the same size. Measuring the absorbance and spectral shift of PPR of metal nanoparticles or nanostructures distributed on a substrate via transmission or reflection to interrogate biomolecular interactions has been demonstrated and now widespread throughout the biochemical research. However, biosensing utilizing scattering properties of nanoparticles is comparatively lacking and less published.

Previously, we have successfully combined the PPR properties of gold nanoparticles (AuNPs) with the superiority of high-flux signal transmission of optical fiber to construct a high sensitivity fiber optic plasmonic sensor, namely FO-PPR sensor. The FO-PPR sensor has been applied to biosensing of real samples such as serum, synovial fluid, and orchid sample. To date, however, the study of interrogating the change of plasmonic light scattering from the surface of fiber optic plasmonic sensor has not been reported yet. Herein, we focus on discussing the possibility of utilizing the scattering power of gold nanoparticles on the FO-PPR sensor in the refractive index (RI) and biochemical sensing applications. The plasmonic scattering mode FO-PPR sensor which relies on the scattering intensity interrogation is experimentally and theoretically demonstrated. The refractive index resolution is estimated to be 3.8x10^?5 RIU. The limit of detection for anti-DNP antibody spiked in buffer is 1.2x10^-9 g/ml (5.3 pM) by using the DNP-functionalized FO-PPR sensor. The image processing of simultaneously recorded plasmonic scattering photographs at different compartments of the sensor is also demonstrated. Results suggest that the compact sensor can perform multiple independent measurements simultaneously by means of monitoring the plasmonic scattering intensity via photodiodes or a CCD. The array-based sensing format on a single fiber by interrogating the change of plasmonic scattering intensity is a specific highlight of this study, since this is not easily achieved with a transmission- or reflection-mode FO-PPR sensor. By exploiting the scattering power of nanoparticles on the fiber surface, the length of detection window can be shortened into several millimeters but with a comparable sensitivity to that of a transmission- or reflection-mode FO-PPR sensor, lowering the obstacle of multiwindow detection on a single fiber. Additionally, it may even be possible to combine with surface-enhanced Raman spectroscopy (SERS) to achieve the goal of monitoring the structural change of the interacting molecules during the sensing process.

8774-8, Session 2

Raman and surface-enhanced Raman scattering (SERS) biosensing *(Invited Paper)*

Marek Prochazka, Charles Univ. in Prague (Czech Republic)

Raman scattering (RS) is a widely used vibrational technique providing highly specific molecular spectral patterns. A severe limitation for application of this spectroscopic technique consists in the low cross section of RS. Surface-enhanced Raman scattering (SERS) spectroscopy overcome this problem by 6-11 order of magnitude enhancement compared with standard RS for molecules in the close vicinity of certain rough metal surfaces [1]. Thus, SERS combines molecular fingerprint specificity with potential single-molecule sensitivity. Due to the recent development of new SERS-active substrates, labelling and derivatization chemistry, as well as new instrumentations, SERS became very promising tool for a wide field of applications, including bioanalytical studies and sensing. Both intrinsic and extrinsic SERS biosensing schemes have been employed to detect and identify small molecules, nucleic acids, lipids, peptides, and proteins, as well as for in vivo and cellular sensing [2, 3]. This contribution gives an overview of recent developments in SERS for sensing and biosensing considering also limitations, possibilities, and prospects of this technique.

[1] E.C. Le Ru, P.G. Etchegoin, Principles of surface enhanced Raman spectroscopy and related plasmonic effects, Elsevier, Amsterdam, 2009.

[2] Surface enhanced Raman spectroscopy: Analytical, biophysical and life science applications, (S. Schlücker, ed.), Wiley-WCH, Weinheim, 2010.

[3] M. Procházka, J. ?t?pánek, Surface-enhanced Raman Scattering (SERS) and its Application to Biomolecular and Cellular Investigation, in Applications of Raman spectroscopy to biology - from basic studies to disease diagnosis (M. Ghomi, ed.), p. 1-30, IOS Press, Amsterdam, 2012.

8774-9, Session 2

Raman-spectroscopy-based biosensing for applications in ophthalmology

Giulia Rusciano, Paola Capriglione, Giuseppe Pesce, Gianluigi Zito, Antonio Sasso, Antonio Del Prete, Giovanni Cennamo, Univ. degli Studi di Napoli Federico II (Italy)

Cell-based biosensors rely on the detection and identification of single cells as well as monitoring of changes induced by interaction with drugs and/or toxic agents. Raman spectroscopy is a powerful tool to reach this goal, being non-destructive analytical technique, allowing also measurements of samples in aqueous environment. In addition, micro-Raman measurements do not require preliminary sample preparation (as in fluorescence spectroscopy), show a finger-print spectral response, allow a spatial resolution below typical cell sizes, and are relatively fast (few s or even less). All these properties make micro-Raman technique particularly promising for high-throughput on-line analysis integrated in lab-on-a-chip devises.

Herein, we demonstrate some applications of Raman analysis in ophthalmology. In particular, we demonstrate the possibility to identify new emerging ocular pathogens such as Acanthamoeba castellanii (A.), an opportunistic protozoan that is widely distributed in the environment and is known to produce blinding keratitis and a fatal encephalitis. Furthermore, by combining Raman analysis with Principal Component Analysis (PCA), we have demonstrated that is possible to distinguish between live and dead cells obtained from eye-microsurgery, enabling, therefore to establish the effectiveness of therapeutic strategies to vanquish the protozoa.

As final step, we have analyzed the presence of biochemical differences in the corneal epithelial tissues of wearers of contact-lenses donors with respect to people not wearing contact lenses. As a matter of facts, more than 85% of Acanthamoeba-keratitis cases occur for people in the first class, suggesting that the use of contact lenses may induce some biochemical alterations of the epithelial tissues, rendering more favorable the binding of the protozoan. The epithelial cells were obtained by 40 volunteers subjected to refractive eye surgery; almost 50% of the donors were wearers of contact-lenses. All the cells were analyzed by Raman spectroscopy within a few hours from the surgery. The results of this analysis and their statistical significance is discussed.

8774-10, Session 2

Surface-enhanced Raman imaging of red blood cell membrane with highly uniform active substrates obtained using block copolymers self-assembly

Gianluigi Zito, Anna Malafronte, Alden Dochshanov, Giulia Rusciano, Finizia Auriemma, Giuseppe Pesce, Claudio De Rosa, Antonio Sasso, Univ. degli Studi di Napoli Federico II (Italy)

Surface-enhanced Raman scattering (SERS) allows analytical ultrahigh sensitive detection of chemical species and the monitoring of time-dependent chemical and biophysical processes thanks to the electromagnetic enhancement induced by nanostructured noble metal surfaces associated with localized plasmon resonances, mainly effective into inter-junctions between metal nanoparticles (NPs), clusters and/or nano-islands of clusters. Silver (Ag) and/or gold (Au) colloidal-based SERS substrates have been largely employed to study chemical and biochemical environments. Although having large enhancement factor, such a kind of substrates do not guarantee high reproducibility and reliable quantitative detection because of the non-uniform morphological distribution of the nanostructured template realizing the surface-enhancement. In this communication, we discuss the application of ordered, ultrahigh-density templates of nanotextured Ag-particles obtained by self-assembling of inorganic-containing polystyrene-block-poly(4-vinylpyridine) copolymer (PS-b-P4VP) micelles. Hexagonal arrays of PS-b-P4VP micelles, with selective inclusion of Ag nanoparticles (NPs) in the polar core, prepared by in situ reduction of a suitable precursor, are obtained by self-assembly, upon fast solvent evaporation during spin coating on a silicon or glass

slide. UV irradiation and/or plasma oxygen treatment remove the polymer matrix leaving immobilized nano-islands of Ag-NPs. Such a kind of SERS-active substrate consists of a reproducible and uniform two-dimensional hexagonal array of silver clusters with a diameter ranging from 20 to 30 nm (single particles having typically diameters of 5 nm) and nano-island gap distances of the order of 5-8 nm, while giving rise to high enhancement factors and addressing the issue of SERS reproducibility. The template is thus applied for surface-enhanced Raman analysis of the red blood cell (RBC) membrane in confocal micro-Raman configuration demonstrating to have SERS imaging potential thanks to the particular nature of the nanotextured substrate.

RBC is usually considered as an ideal system for single cell analysis since it is devoid of nucleus and other organelles and consists of a lipid bilayer membrane with embedded proteins. The membrane, thanks to its high deformability, plays a crucial role in oxygen transfer from blood to tissues in microcirculation. However, in conventional single-RBC Raman experiments the spectra are dominated by hemoglobin (principal content of the cell) and therefore it is quite difficult to isolate the contribution of the membrane.

SERS substrates with high spatial reproducibility are therefore ideal to detect the amplified Raman response originated from the interaction of the membrane with the plasmon excited in our self-assembled Ag-NPs.

Preliminary results are reported on this study. Further research work is in progress to provide an over-cell Raman mapping in short timescale for monitoring real-time chemical processes occurring at the membrane-adsorbed active surface.

8774-11, Session 2

Optical biosensor system with integrated microfluidic sample preparation and TIRF based detection

Eduard Gilli, Sylvia R. Scheicher, Michael Suppan, Heinz Pichler, Markus Rumpler, Valentin Satzinger, Christian Palfinger, Frank Reil, Martin Hajnsek, Stefan Köstler, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria)

There is a steadily growing demand for miniaturized bioanalytical devices allowing for on-site or point-of-care detection of biomolecules or pathogens in applications like diagnostics, food testing, or environmental monitoring. These, so called labs-on-a-chip or micro-total analysis systems (µ-TAS) should ideally enable convenient sample-in – result-out type operation. Therefore, the entire process from sample preparation, metering, reagent incubation, etc. to detection should be performed on a single disposable device (on-chip). In the early days such devices were mainly fabricated using glass or silicon substrates and adapting established fabrication technologies from the electronics and semiconductor industry. More recently, the development focuses on the use of thermoplastic polymers as they allow for low-cost high volume fabrication of disposables. One of the most promising materials for the development of plastic based lab-on-a-chip systems are cyclic olefin polymers and copolymers (COP/COC) due to their excellent optical properties (high transparency and low autofluorescence).

We present a bioanalytical system for whole blood samples comprising a disposable plastic chip based on TIRF (total internal reflection fluorescence) optical detection. The chips were fabricated by compression moulding of COP and microfluidic channels were structured by hot embossing. These microfluidic structures integrate several sample pretreatment steps. These are the separation of erythrocytes, metering of sample volume using passive valves, and reagent incubation for competitive bioassays. The surface of the following optical detection zone was functionalized with specific capture probes (proteins, oligonucleotides) in an array format. The plastic chips comprise dedicated structures for simple and effective coupling of excitation light from low-cost laser diodes. This enabled TIRF excitation of fluorescently labeled probes selectively binding to detection spots at the microchannel surface. The fluorescence of these detection arrays was imaged using a simple set-up based on a digital consumer camera. Image processing for spot detection and intensity calculation was accomplished using customized software. Using this combined TIRF excitation and imaging based detection approach allowed for effective suppression of background fluorescence from the sample, multiplexed detection in an array format, as well as internal calibration and background correction.

Acknowledgement: Financial support by the Austrian Federal Ministry of Transport, Innovation and Technolgy (BMVIT) via the project Biosens is gratefully acknowledged.

8774-12, Session 2

Plasmon-enhanced microcavity biosensing *(Invited Paper)*

Frank Vollmer, Max Planck Institute for the Science of Light (Germany)

Optical microcavities are not only one of the most sensitive approaches for probing the biological world in solution but they are multi-function sensing platforms providing various mechanisms for sizing, trapping, and manipulation at the nano-scale. In particular, Whispering gallery mode

(WGM) biosensors have shown great potential in detecting low concentrations of pathogens, antibodies and other biological molecules and operate by what is known as the reactive sensing principle. Noise levels and achievable mode volumes limit current WGM detection sensitivity however, such that detection of a single protein and other small biomolecules is currently unfeasible. Plasmonic nanostructures grown or deposited on (or near) the WGM resonator surface can produce local intensity hotspots within the sensing domain and hence afford the means to improve detection limit. Using Mie theory we are thus currently theoretically investigating coupling between spheroidal WGM resonators and metallic nanoantennas such as single and multiple gold particles.

Experimental results on protein biosensing suggest that a slight detuning of the plasmon resonance and WGM resonance is optimal for improving detection limits, and we show greatly enhanced sensitivity for BSA sensing in aqueous solutions. We further determine the energy fraction of the WGM field localized at the antenna site, and introduce an efficiency parameter to quantify the field overlap with analyte molecules, a pre-requisite for sensitive detection. By exploiting efficient co-localization of field and analyte in nanopost-antenna arrays, we demonstrate highly sensitive and label-free DNA detection on a broadband chip-scale photonic platform.

8774-13, Session 2

High-performance biosensing on gold nanoparticle arrays

Barbora Spackova, Nicholas S. Lynn Jr., Milan Vala, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Pavel Kwiecien, Ivan Richter, Czech Technical Univ. in Prague (Czech Republic); Jiri Homola, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Biosensors based on surface plasmon resonance (SPR) represent a well-developed technology for the real-time label-free analysis of biomolecular interactions as well as the detection of chemical and biological species. Metal nanostructures supporting localized surface plasmons (LSP) are considered a new generation of substrates for SPR-based biosensing. In contrast to propagating surface plasmons (PSP) supported by thin metal layer, LSPs offer a high degree of localization of an electromagnetic field; however, the optical response to surface RI changes is comparable. In this paper we show theoretically and experimentally that the limit of detection can be considerably improved due to increases in mass-transfer resulting from the decreased footprint of the nanostructure. The presented sensing structure consists of a periodic 2-D array of gold nanoparticles. It exhibits Fano-type resonances, so-called lattice resonances, resulting from the diffractive coupling of light to LSP. The sensing performance is theoretically predicted by numerical simulations pertaining to both the photonic and mass-transfer aspects of the sensor. The structure is produced by 4-beam interference lithography which allows recording periodic nanostructures onto large areas. Index-matching substrate (Cytop) is used to achieve efficient coupling in aqueous solution. To characterize the sensor response, a model experiment is carried out in which short DNA is detected. The results are compared to those obtained using a conventional PSP-based system.

8774-14, Session 2

Electrochemical surface plasmon resonance biosensor for study of DNA desorption and hybridization

Luca Ferrari, Univ. degli Studi di Modena e Reggio Emilia (Italy); Hana Sípová, Ivo Tichy, Karel Chadt, Jiri Homola, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Combination of an SPR biosensor and electrochemical sensor has been recently shown to be a promising tool for biomolecular studies. Moreover, it has been demonstrated that electrochemical SPR biosensors may be more sensitive and specific with respect to detection of target protein or DNA than stand-alone SPR biosensors [1, 2]. In this work we present a system, which combines electrochemical and SPR techniques on the same sensing chip. We explore the optimal design of such system and demonstrate its potential for investigation of DNA hybridization.

The system is based on a four-channel SPR sensor system developed at the Institute of Photonics and Electronics AS CR. Since the SPR system provides four independent channels, an in-situ electrochemical cell has been realized in each channel, allowing four simultaneous electrochemical measurements. The gold substrate used for SPR measurement was used as the working electrode and two further planar gold electrodes (the reference and the counter electrodes) were inserted in the same flow cell. Two different geometries have been proposed; in the first one the working and the reference electrodes are realized on the gold substrate used for the SPR measurement while the counter electrode is realized on the upper part of the flow cell, in the second one only the working electrode is realized on the gold substrate and the reference and counter electrodes are realized in the upper part of the flow cell.

Together with the realization of the electrochemical cells, a custom electronics has been designed and realized. The electronics is able to set an arbitrary potential, in the range -2 to +2 Volt, between the reference and working electrodes and to measure the current flowing between the counter and the working electrodes. Moreover, the electronics is able to drive each cell independently and to select which cell is active, through analog switches.

The electronics is controlled by a software interface in LabVIEW, which allows selecting the active cells and the potentials applied to each cell. Several standard electrochemical techniques are already implemented, i.e. cyclovoltammetry and chronoamperometry. Moreover, the software allows setting a square wave with tunable amplitude (-2 to 2 Volt) and frequency (0.2-2000 Hz).

Preliminary characterization of the electrochemical cells has been performed in buffer solution (PBS 100 mM) with ferricyanide (1 mM) using both the developed cell geometries. A comparison between the acquired electrochemical and SPR signals has been performed.

Furthermore, the electrochemical SPR biosensor was used to study DNA hybridization. By comparing the acquired electrochemical and SPR signals, we show that DNA probes can be desorbed by applying negative potentials to the SPR chip surface. The threshold potential for desorption of DNA probes varies with probe length, probe density and concentration of the salts in the buffer. It is shown that desired probe density can be achieved by optimizing the potential and that potential can be used for regeneration of the SPR chip.

[1] R.J. Heaton, A.W. Peterson, R.M. Georgiadis, Proc. Natl. Acad. Sci. USA, 98 (2001) 3701.

[2] E. Brod, S. Nimri, B. Turner, U. Sivan, Sensors and Actuators B, 128 (2008) 560.

8774-15, Session 2

High Q optical nanobeam cavities for label-free sensing

Muhammad Ghazali Abdul Rahman, Philippe V. F. Velha, Richard M. De La Rue, Nigel P. Johnson, Univ. of Glasgow (United Kingdom)

High Q optical nanobeam cavities are an emerging configuration in many areas of physics and engineering. The applications include sensing due to their ability to detect small index changes of analytes presence in the active region. The index changes correlate with the presence of different chemical in the analytes. Here, we present design, modeling, fabrication, and experimental results for silicon-on-insulator (SOI) nanobeam cavities. The sensing properties of the device depend on the sharpness of the resonance peak (Q-factor) and achievable resonance wavelength shifts. We present a simple optical technique for detection based on nanobeams that gives good sensitivity for various chemicals. Confining the light in the cavity mode and overlapping it with the analyte in the active region give the optimum sensitivity. The removal of the silica lower cladding from underneath the nanobeam cavities not only increases the Q-factor but also the sensitivity, because more analyte overlaps with the cavity modes. We investigate the sensing properties of both silicon on a lower silica cladding layer and silicon-on-air (membrane) platforms.

8774-16, Session 2

Optical sensors for therapeutic drug monitoring of antidepressants for a better medication adjustment

Anne K. Krieg, Günter G. Gauglitz, Eberhard Karls Univ. Tübingen (Germany)

During the last decades therapeutic drug monitoring (TDM) is getting more and more important. By monitoring the serum level of drugs or their metabolites it has been shown that people tolerate medication differently. Some people are degrading drugs faster than others and therefore the medication dose should be adjusted individually [1]. This can reduce the number and intensity of side-effects which is a big issue in the field of psychotropic medication. As tricyclic antidepressants (TCA) are common in the treatment of depressions they are chosen for further investigations.

Using optical sensor devices for detection and quantification [2] provide a fast, affordable, miniaturizable and easy to use technique to monitor a wide range of therapeutic drugs.

In this work an immunoassay for the antidepressant Amitriptyline is presented using the direct optical method Reflectometric Interference Spectroscopy (RIfS) [3]. It is a simple, robust and label-free method for direct monitoring of binding events on glass surfaces. The incident white light is partially reflected at the interfaces of the glass transducer and the sensitive layer resulting in an interference spectrum that depends on changes of the optical thickness of the top layer. The optical thickness hinges on refractive index and physical thickness. Due to the time-resolved observation of binding events kinetic and thermodynamic constants of associating/dissociating binding partners (e.g. antigen/antibody) can be determined.

The binding inhibition test has been chosen as assay format and therefore the recognition element (antigen) is immobilized on the sensor surface [4]. The antigen has to be bound to a surface with the right epitope still accessible for the antibody to recognize and bind. For this immunoassay an Amitriptyline derivative (Nortriptyline) is immobilized on a glass transducer by standard surface chemistry on top of an aminodextrane (AMD) layer. This AMD layer should shield the surface against unspecific binding of blood components. The essential part of the molecule that is recognized by the antibody is still available for binding.

For each measurement a defined amount of specific antibodies is added. They are binding to the antigen on the surface unless the binding is inhibited by free Amitriptyline in a sample. No fluorescent label is needed making the whole assay less expensive than label-based methods. With this recently developed immunoassay concentrations in buffer (PBS) down to 500 ng/L can easily be detected. The concentration-dependent binding signal is reproducible and can be calibrated. Each glass transducer can be regenerated several times after measurements.

During the pending investigations it will be verified whether the developed Amitriptyline assay shows good values for LOD/LOQ in real blood samples, too. The results of the assay will be compared with validated clinical methods.

Small and affordable assay devices for psychotropic medication will raise the number of individual TDM in psychiatric clinics [5]. Unpleasant side-effects are reduced and the physical comfort of patients increases.

Literature:

[1] S.M.R. Wille et al., Crit Rev Cl Lab Sci (2008), 45(1), 25-89.

[2] G. Gauglitz, Anal Bioanal Chem (2010), 398(6), 2363-2372

[3] G. Proll et al., Reflectometric Interference Spectroscopy, Humana Press 2009.

[4] C. Albrecht et al., Anal Bioanal Chem (2008) 391:1845–1852

[5] G. Laux et al., J Neural Transm (2007), Suppl 72, 261-267.

8774-17, Session 3

Recognition as a challenge in label-free optical sensing *(Invited Paper)*

Günter G. Gauglitz, Eberhard Karls Univ. Tübingen (Germany)

Optimizing label-free optical sensing for a variety of applications in the area of environmental analysis, health care, and food safety depends on recognition elements, quality of the interaction layer, detection principles, and evaluation strategies. Thus, nonspecific interaction sample/transducer have to be reduced, recognition selectivity improved, and a suitable detection method selected. For this reason, strategies to avoid non-specific interaction even in blood or milk are discussed. A variety of up-coming recognition elements is given. Based on the classification of direct optical detection methods some examples for the above mentioned applications are reviewed. Trends as well as advantages of parallel multi-spot detection for kinetic evaluation will close the lecture.

8774-18, Session 3

Optical biosensors for the label-free detection in complex biological media

Eduard Brynda, Tomas Riedel, Andrés de los Santos Pereira, Cesar Rodriguez-Emmenegger, Institute of Macromolecular Chemistry of the ASCR, v.v.i. (Czech Republic)

Unfavorable ratio between sensor responses to the analyte binding and to the fouling from complex biological fluids, such as, blood plasma or serum, is still an essential barrier to applications of label-free detecting affinity biosensors in medical diagnostics.

Gold surfaces of SPR transducers were coated with self-assembled monolayers (SAM) of di- or hexa-(ethylene glycol) undecanethiol (EG2 or EG6) and polymer brushes of poly(2-hydroxyethyl methacrylate) (poly(HEMA)), poly(oligo ethylene glycol methacrylate) (poly(OEGMA)), and poly(hydroxypropyl methacrylamide) (poly(HPMA)) prepared by the surface initiated atom transfer radical polymerization. The potential of the coatings for the detection in blood plasma, serum, and milk was estimated.

The fouling (ng cm-2) from undiluted blood plasma was 120 on EG2, 76 on EG6, 12 on poly(OEGMA), 11 on poly(HEMA), and below the SPR detection limit of 0.03 on poly(HPMA). An immunosensor for the detection of G Streptococcus was prepared by covalent immobilization of the respective antibodies on poly(HPMA) coated SPR chip. A biosensor with three specific antigens immobilized on poly(OEGMA) was able to detect antibody markers characteristic for various stages of EB virus infection in real clinic serum samples.

The fouling (ng cm-2) from fresh-whole fat milk was 45 on EG2, 2.7 on EG6, 3.4 on poly(OEGMA), and undetectable on poly(HEMA). A new immunosensor for the detection of a pathogen bacteria, Cronobacter, fresh milk a powdered infant milk formulations was prepared by covalent immobilization of the respective antibodies on poly(HEMA) coated SPR chip.

8774-19, Session 3

UV-light-assisted functionalization for sensing of light molecules

Riccardo Funari, Univ. degli Studi di Napoli Federico II (Italy); Bartolomeo Della Ventura, Univ. degli Studi di Roma La Sapienza (Italy); Luigi Schiavo, Rosario Esposito, Carlo Altucci, Raffaele Velotta, Univ. degli Studi di Napoli Federico II (Italy)

In recent years there is a strong interest in the development of biosensors for sensitive and rapid detection of pollutants. One of the main issues of this research topic is the immobilization of the biological sensitive elements on the sensor surface. A novel functionalization technology is the so-called photonic immobilization technique (PIT) which is very effective in developing QCM (quartz crystal microbalances) based immunosensors. PIT consists of irradiation of antibodies in solution ultrashort UV laser pulses. The activation involves the structural triads Trp/Cys-Cys, highly conserved in immunoglobulin superfamily, in which the UV absorption causes the breakage of the disulfide bridge and the production of the free thiol groups. These new chemical functions can interact with a gold lamina orienting the adsorbed antibody with its antigen-binding sites well exposed to the environment. This technique has been used to functionalize the gold electrodes of a QCM in order to develop an immunosensor against the parathion, a forbidden pesticide, resulting in a huge increase of the sensitivity. The main drawback of QCM technology in detecting light analytes like parathion (300 Da) is the small frequency shift associated with the antigen-binding process. This problem is overcome labeling the organophosphate molecule with the BSA (bovine serum albumin). This protein binds the parathion by means of unspecific interactions thereby making the analyte "heavier" and well-detectable by a QCM. The measurements are not affected by this unconventional labeling because the sensor is insensitive to BSA when the gold lamina is functionalized. Using this procedure, a limit of detection of 4 ppb was achieved with a measurement requiring less than 10 minutes. The sensor shows little if any response against different compounds so the photonic activation does not affect the specificity of the adsorbed antibodies. Since PIT only requires the presence of the structural triad Trp/Cys-Cys, this technique can be very useful in the functionalization of any thiol reactive surface.

8774-21, Session 3

Optical sensors based on metal oxide nanowires for UV/IR detection

Jose Luis Pau Vizcaíno, Carlos García Nuñez, Antonio García Marín, Eduardo Ruiz, Juan Piqueras, Univ. Autónoma de Madrid (Spain)

Nanotechnology tools and materials have introduced new possibilities for the design and fabrication of electron devices and integrated circuits (IC). The reproducibility of nanostructure synthesis and the ways in which those structures are integrated in the IC processing are major issues for the massive commercialization of nanoelectronic devices with superior performances.

Barry Hendy of Kodak Australia plotted the "pixels per dollar" as a basic measure of value for a digital camera, demonstrating the historical linearity (on a log scale) of this market and the opportunity to predict the future trend of digital camera price and resolution; but, as in Moore´s law, this trend will start saturating as we approach the limits of miniaturization. Thus, new technologies and concepts will be needed to face future progress of digital imagers the same as the electronic industry.

Metal oxide nanowires present high stability and excellent optical, electrical and mechanical properties. Their synthesis is cost-effective since they can be produced by means of conventional ovens using vapor phase transport. The crystal quality of these nanowires is superior to that found in thin films due to the lack of strain during growth which prevents the formation of defects as the structure relaxes.

In this work, ZnO and CuO nanowires are produced and reproducibly deposited between prepatterned electrodes by dielectrophoresis. Highly selective UV detection is demonstrated in n-type ZnO nanowire photoconductors. High photoconductive gains are achieved along with a slow response induced by surface effects. The results indicate that the reduction of the nanowire diameter improves the dynamic range of the sensor, limiting the dark current level. Therefore, it seems that the charge remains confined near the center of the nanowire and far from the sidewalls. This property allows us to conceive impact ionization devices based on high crystalline ZnO nanowires since the built-in surface voltage reduces the probability of surface breakdown. On the other hand, cupric oxide (CuO) is known to be a p-type semiconductor with a band-gap of 1.2-1.9 eV. Therefore, the integration of both types

of nanowires allows the formation of heterojunctions with potential application in optoelectronics, as well as ICs with dual UV/IR sensing capabilities.

The effects of the electrical contact between the nanowire and the electrodes are discussed. Electrodes based on transparent conductive oxide are used to improve the electrical contact. Through surface modification, self-assembled monolayers are formed on the nanowire surface aiming to analyze the effects on the sensor performance. Au nanoparticles are attached to the nanowires aiming to enhance the device responsivity.

8774-22, Session 4

Surviving mRNA detection by means of optical fiber nanotips coated with molecular beacons

Ambra Giannetti, Andrea Barucci, Sara Tombelli, Cosimo Trono, Franco Cosi, Istituto di Fisica Applicata Nello Carrara (Italy); Giancarlo C. Righini, Istituto di Fisica Applicata Nello Carrara (Italy) and Museo Storica della Fisica e Ctr Studi e Ricerche Enrico Fermi (Italy); Stefano Pelli, Francesco Baldini, Istituto di Fisica Applicata Nello Carrara (Italy)

In this paper we present a molecular beacon used as bioreceptor for mRNA detection immobilized onto the distal end of a tapered fiber. Molecular beacons (MB) are single-stranded DNA molecules that possess a stem-and-loop structure. It is labeled with a fluorophore and a quencher on the two ends of the stem. Since the stem keeps these two moieties in close proximity to each other, it causes the fluorescence of the fluorophore to be quenched by energy transfer. Moreover, since the loop portion of the molecule can form a double-stranded DNA in the presence of a complementary sequence, the fluorophore fluorescence is restored when the MB hybridizes to the target sequence.

In particular, the fluorophore and the quencher chosen are ATTO647N and the BlackBerry Quencher (BBQ), respectively. The fluorescence of ATTO647N is excited most efficiently in the range 625 - 660 nm. A suitable excitation source is the 647 nm line of the Krypton-Ion laser or a diode-laser emitting at 650 nm. The emission wavelength is at about 670 nm. BBQ has its useful absorbance between 550 and 750 nm.

In our work, the attention was focused on the mRNA for survivin, a protein highly expressed in most types of cancer. Survivin-MB was characterized by hybridization studies with a complementary sequence to prove its functionality both free in solution and once immobilized onto the fiber tip. The nanotips were fabricated by chemical etching, starting from 500 micron diameter multimode optical fiber and tapering it down to about 100 nm at the tip. Next, the MB was attached to the nanotips via covalent binding. In particular, a silanization procedure of the tip was performed. 3-Aminopropyltrimethoxysilane (APTMS) was used in order to have amino-groups available for the immobilization of the MB which was properly synthesized with a –SH group in the 3' end. The crosslinker N-succinimidyl 3-(2-pyridyldithio) propionate (SPDP) was used since it is capable to form amine-to-amine or amine-to-sulfhydryl crosslinks among molecules forming disulfide-containing linkages. Then the fluorescence of the MB fluorophore was externally collected after direct excitation through the optical fiber ending with the tip. The MB coated nanotips are proposed as innovative tool for entering the cytoplasm of living cells, and directly measure the intracellular RNA.

8774-23, Session 4

Feasibility study of an IgG/anti-IgG label-free bioassay based on long period grating

Francesco Chiavaioli, Francesco Baldini, Cosimo Trono, Ambra Giannetti, Massimo Brenci, Riccardo Falciai, Istituto di Fisica Applicata Nello Carrara (Italy)

Optical fiber gratings, especially long period gratings, have been lately proposed as effective label-free tools for chemical and biochemical sensing. A change in refractive index can be induced by a biochemical interaction taking place along the grating area, and thus yielding a change in the transmission spectrum of the fiber. This provides an alternative methodology with respect to other label-free optical approaches, such as surface plasmon resonance, interferometric configurations and optical resonators. Instead of the commonly used silanization procedure, the functionalization of the fiber has been implemented using Eudragit L100 copolymer. The stability test of the deposited copolymer layer has been checked by pumping a phosphate-buffered saline (PBS) solution at constant rate for more than 4 hours. In addition, in order to confirm the uniform coverage of the biolayer along the optical fiber , measurements of the fluorescence emitted by the layer deposited on the fiber were performed after the implementation of a first bioassay carried out with Cy5-labeled anti-IgG. Afterwards, a second label-free IgG/anti-IgG bioassay has been carried out in order to analyze the antigen/antibody interaction. The performed study allowed to follow the kinetics during the antibody immobilization and the antigen interaction at different concentrations in order to achieve the calibration curve of the bioassay, from which it is possible to calculate the characteristic parameters of the biosensor. Finally, a comparison of the sensor performance was made using two different long period gratings with distinct pitches in the refractive index modulation. As expected, experimental results proved that the shorter the grating period is, the higher the coupled cladding mode is, and the better the biosensor performance is. Considering a long period grating manufactured on a bare optical fiber, in which the coupling occurs between the fundamental core mode and the 7th cladding mode, a dynamic signal range of 322 pm, a working range of 1.7 – 1450 mg L-1 and a LOD of 500 ?g L-1 have been achieved.

8774-24, Session 4

Electric charge measurements of a single bacterial spore

Giuseppe Pesce, Giulia Rusciano, Antonio Sasso, Univ. degli Studi di Napoli Federico II (Italy)

Many key properties of colloidal suspensions are directly or indirectly controlled by the electrical charge carried by their constituent particles. In biology, the role of the charge carried by a single cell has relevant effect on a variety of phenomena like the aggregation of red blood cells, the adhesion on planar surfaces, the uptake of molecules. Consequently, methods to measure the electrophoretic mobilities of colloidal particles have received a lot of attention during the last couple of decades.

For many years charged colloidal systems have been extensively studied with electrokinetic techniques such as electrophoresis and dielectrophoresis extended also at microscales by combining microfluidic devices with arbitrarily shaped microelectrodes.

The zeta potential of the colloidal probe is a parameter of great importance, nevertheless it is often poorly quantified. Indeed, measurements using commercial zeta potential equipment based on dynamic light scattering typically reach an accuracy of 5%– 10% and are generally ensemble-averaged values of colloidal solution and hence neglect the variance encountered in single particle measurements.

Optical tweezers systems represent a very powerful alternative because they enable one to trap a single particle without any mechanical contact and to measure its position and the forces acting on it with high resolution. Thus they are widely used in colloidal as well as in biophysical research [1].

Here we show how the charge carried on by a single particle can be determined using an optical tweezers when a known external electric field is applied. Tracking the small displacements of the trapped probe around the equilibrium position it is possible to separate the thermal motion and the deterministic motion caused by the external field. These two contributions can be accurately evaluated by calculating the autocorrelation function of the particle position which results in the superposition of an exponential function, depending on the trap stiffness and hydrodynamic factor, and a sinusoidal function, depending on the applied field and the effective charge of the particle which can be determined with a sensitivity al level of the elementary charge.

We apply this technique to measure the charge carried on by a single bacterial spore (Bacillus Subtilis) which are very promising natural vehicle for drug delivery application. We study how the charge changes when the wild type spore surface is mutated and how the different charge can play a role for efficient protein transportation.

[1] G. Pesce et al."Mapping electric fields generated by microelectrodes using optically trapped charged microspheres", Lab-on-a-chip 11, 4113-4116

8774-25, Session 5

Basic structures of integrated photonic circuits for smart biosensor applications

Susette Germer, Helmholtz-Zentrum Dresden-Rossendorf e.V. (Germany); Charaf A. Cherkouk, Helmholtz-Zentrum Dresden-Rossendorf e.V . (Germany); Lars Rebohle, Manfred Helm, Wolfgang Skorupa, Helmholtz-Zentrum Dresden-Rossendorf e.V. (Germany)

The definition of sensors includes all aspects of optical devices from source and detection technologies, integrated sensor configurations and processing approaches to applications for environmental or biochemical control and medicine. Especially bio sensing needs systems that incorporate electronic and photonic devices for the detection of harmful substances. We present recent developments in the integration of Si-based light emitters into a photonic circuit for a planar optical waveguide-based bio detection system. In our first approach we deal with the integration of a Si-based light emitting device (LED) into a photonic circuit for the detection of harmful biological substances. Commonly, external sources coupled to the waveguide by an optical fibre, a microscope objective or a prism, were used to achieve light injection into the sensor system by total internal reflection. For simplifying this injection process, we built Si-based LEDs which have a metal-oxide-semiconductor (MOS) structure, in which the oxide film contains group-IV and/or rare earth elements, incorporated by ion-beam synthesis [1, 2]. These LEDs exhibit strong electroluminescence, tunable from the visible up to the UV region depending on the rare-earth element (e.g. Gd, Tb, Eu, Nd, Er). Currently, LEDs based on Tb or Er achieve external quantum and power efficiencies in order of 16% and 0.3% and showed their potentials as internal light sources in a microfluidic cell plate for endocrine disrupting chemical (EDC) detection, like estrogenic activity, in waterish solution [3]. Our recent concept bases upon a Si-based photonic circuit which consists of the integrated LED, a newly fabricated dielectric strip-waveguide below a bioactive layer and a receiver. The dielectric strip-waveguide has a Si3N4 or SiON core in which the light should be guided, and a cladding of SiO2. The receiver should be a photodiode (e.g. Ge, Si). In this work, we concentrate on the development and characterization of the dielectric waveguides. For the theoretical pre-calculations we are using finite element simulation software. The mode profiles and resonance frequencies were calculated according to the cross sections of the structures with the software FlexPDE. The fabrication of the waveguides was done by plasma enhanced chemical vapour deposition (PECVD), photolithography and electron beam lithography. Manufactured waveguides were analyzed by scanning electron microscope (SEM). Obtained SEM results enabled an improvement of the fabrication recipe of the waveguides by using an additional Al-masking during the reactive ion etching (RIE), which protects against undercutting and allows better defined waveguide structures Additionally, we built up a new measurement setup, which enables transmission measurements, inspection of the beam profile and determination of the damping factors of the fabricated waveguides in dependence on their cross sections via end-fire coupling. In future, the theoretical calculations are going to be compared with the experimental results of transmission and beam profiling measurements. Moreover, the Si-based LED should be coupled with the waveguide e.g. by Bragg grating. Finally, this lab-on-a-chip system is showing a high potential to become an all-round applicable integrated sensor system, without using any external

light sources or relay lenses, which is why it should be easily portable and customizable. [1] L. Rebohle, C. Cherkouk, S. Prucnal, M. Helm, W. Skorupa, Vacuum 83, 24 (2009) [2]] L. Rebohle, T. Gebel, R.A. Yankov, T. Trautmann, W. Skorupa, J. Sun, G. Gauglitz, R. Frank, Optical Materials 27, 1055 (2005) [3] C. Cherkouk, L. Rebohle, S. Howitz, W. Skorupa, Procedia Engineering 25, 1185–1188 (2011)

8774-26, Session 5

Photoinduced absorption measurement on a microchip equipped with organic dye-doped polymer waveguide

Takashi Kawaguchi, Kouji Nagai, Kenichi Yamashita, Kyoto Institute of Technology (Japan)

Optical sensing on a compact microchip is expected as a convenient means for detections or measurements of environmental substances and biomaterials. Functionality of the optical microchips would be diversified with developing the miniaturization technology of various optical components such as the light sources, lenses, waveguides, microfluidic channels, and light detectors. At present, the most popular scheme for material detection is emission measurement. However, it is usually required in the emission measurements that the materials to be detected are labeled by fluorescent molecules as the marker. To cover this weak point, label-free sensing schemes have been investigated intensively, such as absorption and interference spectroscopies. It should be noted that these methods require an incoherent light with wide spectrum as the probe light.

In this study, we have fabricated a waveguide-type optical sensing microchip and achieved the on-chip measurement of photoinduced absorption (PIA). The PIA microchip developed here was fabricated with a conventional photolithographic technique and consisted of plastic waveguides and microfluidic channels on a silicon substrate. Furthermore, an organic dye-doped polymer waveguide was integrated on this microchip, which is used as a probe light source with wide spectrum. This device was a serially cascaded dye-doped polymer waveguide and could be fabricated with our recent technique, self-written active waveguide technique. At the operation, the dye-doped polymer waveguide was optically pumped in pulses by using a UV light-emitting diode or a laser diode. The pulsed emission from the dye-doped waveguide was guided to the microfluidic channel, which had a wide spectrum and used as the probe light. At the same time, liquid sample injected into the microfluidic channel was optically pumped synchronously. The light transmitted through the liquid sample was detected by a CCD multichannel spectrometer. Then the transmission spectrum of the minute test body under the optical excitation was obtained, and the PIA signal could be detected. In this study, we have examined the on-chip PIA measurements for two kinds of samples, chlorophyll b and neodymium(III) acetate hydrate. In the measurement for the chlorophyll b, the absorption peak around the Q band showed photoinduced decrease in the intensity. Since this result was as similar as the well-known feature of chlorophyll b observed in a conventional PIA system. On the other hand, the PIA spectrum of the neodymium(III) acetate hydrate showed increase in the 4f-4f absorption intensity. The origin of this PIA signal might be the change in oscillator strength at the excited condition. From these results, we expect that this type of microchip analysis will promise as one of the label-free sensing schemes.

8774-27, Session 5

Lab on fiber by using the breath figure technique

Marco Pisco, Giuseppe Quero, Univ. degli Studi del Sannio (Italy); Agostino Iadicicco, Univ. degli Studi di Napoli Parthenope (Italy); Michele Giordano, Francesco Galeotti, Consiglio Nazionale delle Ricerche (Italy); Andrea Cusano, Univ. degli Studi del Sannio (Italy)

Recently, the realization of miniaturized and advanced optical fiber devices and the related development of technological processes, specialized for the optical fibers, led to the definition of the "Lab on Fiber" concept [1], devoted to the realization of novel and highly functionalized technological platforms completely integrated in a single optical fiber for communication and sensing applications.

In this scenario, the creation of micro and nanostructures on the end facet of optical fibers is of great interest because it may yield versatile optical devices well-suited to serve as miniaturized probes for remote sensing applications.

Several approaches have been recently introduced to fabricate metallic

and dielectric structures on the optical fiber end facet.

Some approaches relies on the study of appropriate techniques to transfer planar nano-scale structures, fabricated on a planar wafer by means of standard lithographic techniques, onto the optical fiber end facet. These methods exploit well-assessed fabrication processes developed for planar substrates, but they are limited by the final transferring step that plays a fundamental role in determining both the fabrication yield and the performance of the final device.[1]

Alternative approaches are based on direct-write patterning of the fiber tip. These methods are able to efficiently provide nanostructured devices on the optical fiber, but they require complex and expensive fabrication procedures with a relatively low throughput [2].

In this work, we present recent results on the fabrication of metallo-dielectric nanostructures on the optical fiber tip for sensing applications by using a self-assembly technique. Our studies aim to attain advanced nanostructured sensors by exploiting easy and low cost fabrication processes suitable to be employed in massive production of technologically advanced optical fiber sensors.

The pursued approach basically consists in the preparation of a patterned polymeric film by the breath figure (BF) technique, directly on the optical fiber tip, and in the subsequent metal deposition by evaporation.

We fabricated several prototypes of miniaturized sensing probes by employing the cleaved end of a standard single mode optical fiber embedded in a ceramic ferule as substrate.

The experimental results demonstrate the successful creation of a honeycomb pattern on the optical fiber tip.

Morphological analysis demonstrate that the patterns are regular and highly ordered. In the different realized samples, the holes present a cavity diameter ranging from 0.8 up to 2.0 μm and the distance between two contiguous centers (pitch) ranges from 1.7 up to 3.2 μm.

Spectral analysis in reflectance reveals the presence of broadband dips as function of the morphological properties.

The sensing properties of the nanostructured probes have been also investigated in terms of sensitivity with respect to the surrounding refractive index changes for chemical and biological sensing applications.

The experimental results demonstrate the feasibility of the proposed approach for the realization of miniaturized sensing

probes in the roadmap of "Lab on fiber" technology development.

1. A. Cusano et al., Proc. SPIE, vol. 8001, 800122 (2011).

2. M. Consales et al., ACS Nano, VOL. 6 ' NO. 4 ' 3163–3170 ' 2012.

8774-28, Session 6

Migrating the Mach-Zehnder chemical and bio-sensor to the mid-infrared region

Lothar Leidner, Melanie Ewald, Eberhard Karls Univ. Tübingen (Germany); Markus Sieger, Boris Mizaikoff, Univ. Ulm (Germany); Günter G. Gauglitz, Eberhard Karls Univ. Tübingen (Germany)

Integrated optical phase-modulated Mach-Zehnder interferometers (MZI) are widely used in telecommunication applications. They are highly sensitive to changes of index of refraction. Therefore in the early 1990s their potential to act as chemical or biological label-free sensor was detected. With one arm of the MZI structure coated and leaving an open sensor window on the other arm, the structure becomes sensitive to changes of the effective refractive index, when e.g. an analyte solution is dropped onto the sensor window (evanescent field effect). Changes of refractive index can be monitored online by evaluating the resulting interference pattern.

An early application of the MZI principle is a gas sensor [1]. The window arm is covered by a polysiloxane layer, sensitive to organic solvents. The refractive index of the polymer changes as gas molecules diffuse into the layer. In another application the MZI sensor is used to establish an immunoassay for the detection of the herbicide simazine [2]. The spectrum of possible applications is nearly unlimited. Most if not all sensors of MZI type operate at wavelengths of the visible or near infrared spectrum. As the sensitivity increases with decreasing wavelength this seems to be a good choice.

However, there are several reasons to change this strategy and move into the mid-infrared spectral range (MIR).

- According to the longer wavelength the MIR is more tolerant to manufacturing inaccuracies.

- The evanescent field penetration depth is in the order of ?m allowing insight into bigger structures (bacteria)

- Application of surface enhanced infrared absorption effect (SEIRA) on MZI waveguide surfaces acts as signal amplification by noble metal nanostructured surfaces. Together with the enhanced penetration depth an improved (lowered) limit of detection (LOD) is to be expected.

- Fingerprints allow identification of subspecies in cases, where the pre-selection by the assay setup is not selective enough.

The basis of the planned MIR-MZI is a GaAs waveguide pattern epitaxially grown on a substrate [3]. As a first step towards nanostructuring the waveguide surface, chemical deposition of Au nanoparticles on GaAs transducers was established. For the use of MIR-MZI sensors in bioanalytical assay development, chemical immobilization of molecular recognition elements on GaAs transducers was carried out. The modified surfaces were analyzed with atomic force microscopy (AFM) and dark field microscopy. Furthermore, contact angles and ellipsometric data were determined. Moreover, the prepared surfaces were characterized in the visible spectral range via a modified version of Reflectometric Interference Spectroscopy (RIfS) [4]. It was possible to monitor both the immobilization of gold nanoparticles and time-resolved specific binding of a model antibody to an appropriate model antigen on the modified GaAs surface.

After successful setup of relevant assays with RIfS, for example the detection of bacteria or endocrine disruptors, the assays are designed to be transferred onto the mid-infrared Mach-Zehnder interferometer.

Literature:

1. N. Fabricius, G. Gauglitz and J. Ingenhoff (1992): Sensors und Actuators B. 7, 672-676

2. B. Drapp, J. Piehler, A. Brecht, G. Gauglitz, B.J. Luff, J.S. Wilkinson, J. Ingenhoff (1997), Sensors and Actuators B 38-39, 277-282

3. M. Sieger, F. Balluff, X. Wang, S.-S. Kim, L. Leidner, G. Gauglitz, B. Mizaikoff, Anal. Chem., 2012 accepted for publication.

4. G. Gauglitz (2005), Anal Bioanal Chem. 381(1), 141–155

8774-29, Session 6

Differential length measurement using low-coherence tandem interferometry

Martin D. Smith, William N. MacPherson, Robert R. J. Maier, Heriot-Watt Univ. (United Kingdom)

This paper presents the use of low coherence tandem interferometry for the measurement of differential cavity lengths.

The novel all-optical fibre based sensing configuration has been designed to measure the changes in differential length of two independent Fabry-Perot (F-P) type micro-cavities at widely separated locations in an environment where strong temperature gradients may exist. The two discrete F-P type micro-cavities are formed between the cleaved end of a fibre and a reflective surface which could, for example, be a pressure sensing membrane or any other component of a transducing element.

The sensing system is based on two cavities arranged sequentially in tandem. The lengths of the cavities are probed by a temperature stabilised fibre based Michelson interferometer. The fibre lengths of the probing interferometer are matched in length to within a few 10's of microns and the ends of the fibres are mirrored to form the high reflective ends of the Michelson's arms. One arm of the probing Michelson interferometer is scanned using a piezo fibre stretcher, resulting in an optical path length difference (OPD) between the two arms. The output of the interferometer is connected to the tandem arrangement of the micro-cavities.

The light source used is a super luminescent diode centred at 1550nm, with a -3dB bandwidth of 60nm, resulting in interference fringes being observed at the output of the optical system when the path length imbalance in the Michelson interferometer is equal to the modulus of the difference in length of the two sensing cavities, L1 and L2. A further signal is recorded when the arm lengths of the Michelson interferometer match. Therefore, through measuring the required fibre stretch between achieving a matched OPD in the Michelson and the modulus of the cavity difference, the required measurand can be determined.

The optical interconnecting leads from the probing Michelson interferometer to the two F-P locations are not an active part of the sensor configuration and therefore this configuration is largely insensitive to temperature and strain effects on these interconnecting leads. It is only the probing Michelson interferometer which has to be temperature stabilised. This arrangement allows the F-P measurement cavities to be separated by large distances, and therefore has possible applications in experimental tests which require the precision of differential interferometry without the temperature and stability constraints often required.

In this paper, we demonstrate an approach for the differential length measurement of two Fabry-Perot micro-cavities with a distance separation between the two of tens of meters, using an all optical fibre arrangement, which is virtually insensitive to temperature effects on the interconnecting leads connecting the two widely separated cavities.

8774-30, Session 6

New optical probe approach using mixing effect in planar photodiode for biomedical applications

Tania Pereira, Pedro Vaz, Tatiana Oliveira, Ines Santos, Adriana Leal, Vania Almeida, Helena Pereira, Carlos Manuel B. A. Correia, João M. R. Cardoso, Univ. de Coimbra (Portugal)

The laser diode self-mixing technique is a well-known and powerful interferometric technique that has been used in biomedical applications, namely for the extraction of cardiovascular parameters. However, to construct an optical probe using the self-mixing principle, able to acquire signals in the human carotid artery, some problems could be expected. The laser diode has a small aperture area, which means that, for physiological sensing purposes, it can be considered as a point-like detector. This feature imparts difficulties to recording good quality physiological signals since the number of photons collected and mixed in the cavity of the photodiode is very small. In order to circumvent this problem, a new mixing geometry based on an external large area planar photodiode (PD) is used in the probe, enabling a much larger number of photons to be collect, hence improving the quality of the signal. In this work, the possibility to obtaining the mixing effect outside the laser cavity using an external photodetector, such as a planar photodiode, is demonstrated. Two test benches were designed, both with the presence of two reflectors. The first one, which reflects the light beam with the same frequency of the original one, is fixed and the second one, is movable, reflecting the light to the photodetector with a Doppler shifted frequency. The first test bench has a fixed mirror in front of the movable mirror, creating an umbra and penumbra shadow above the movable mirror. To avoid this problem, another test bench was constructed. This one uses one wedged beam splitter (WSB) instead of a fixed mirror. This new assembly ensures the separation of a single input beam into multiple copies that undergoes successive reflections and refractions. Some light waves are reflected by the planar surface of WSB, while other light beams are transmitted throw the WSB, reaching the movable mirror. Also in this case, the movable mirror reflects the light with a Doppler frequency shift, and the PD receives both beams. The two test benches were designed to demonstrate that it is possible to obtain mixing effect outside the laser cavity, using a planar photodiode. The Doppler spectrograms from the signals acquired in the test benches show that the signal frequency changes along time which correspond to the modulus of the derivative of the mirror movement, as expected in the self-mixing signals. Nevertheless, the test bench I showed better results than the test bench II. This fact probably results from the attenuation that the original beam suffers in each reflection and refraction in the WBS. Tests developed in the test benches opened the possibility to construct a probe that uses a planar photodiode with a large area to collect medical signals, and improve the quality of the acquisition with a better SNR.

8774-31, Session 7

Amorphous silicon balanced photodiode for microfluidic applications

Domenico Caputo, Giampiero de Cesare, Riccardo Scipinotti, Augusto Nascetti, Univ. degli Studi di Roma La Sapienza (Italy)

In this paper, we present the integration of an amorphous silicon balanced photosensor with a microfluidic network to perform on-chip detection with high dynamic range in biomedical applications. By using conventional photodiodes, a trade-off between input signal dynamic range and resolution has to be found. The balanced photodiode, instead, permits to increase the dynamic range and the sensitivity of the measurement by rejecting the any common mode signal, as background photocurrent.

The balanced photodiode is constituted by two series-connected a-Si:H/a-SiC:H n-i-p stacked junctions, deposited by Plasma Enhanced Chemical Vapor Deposition on a glass substrate. The light impinges on the two diodes through a metal grid shaped electrode. The structure is a three terminal device, two of which bias the diodes in reverse conditions while the third electrode (i.e. the connection node of the two diodes) provides the output signal given by the difference between the currents flowing through the two diodes. The 2x2mm2 area devices have been fabricated with a four-mask process in order to define the bottom electrodes of the diodes, the sensor area, the insulation layer and the top metal grid over the sensors. Device characterization, performed both in dark conditions and under 365 nm monochromatic ultraviolet radiation, measured differential currents three orders of magnitude lower than the average current flowing in each sensor. Common mode rejection ratio (CMRR) values around 42 dB have been calculated with no significant variations with both the reverse bias voltage and the radiation intensity.

The microfluidic network has been fabricated by molding two PolyDimetilSiloxane (PDMS, Sylgard 184 from Dow Chemicals) channels with dimensions of 3cm x 2mm x 150 ?m (L x W x H) for each channel. The internal surface of the channels has been treated with PolyEthylene Glycol (PEG) to turn the PDMS hydrophobic properties into hydrophilic properties and thus to allow capillarity flows in the channels.

After fabrication the network has been positioned directly on the glass surface over the balanced photodiode aligning each diode with a channel. This configuration guarantees optimal optical coupling between luminescence events occurring in the channels and the photosensor.

The experiments have been carried out measuring the differential current in several conditions: a. no water in both channels; b. water only in one channel; c. water in one channel and solution containing fluorescein in the other channel. All the experiments have been executed under a large background light intensity to reproduce realistic operating conditions in biomedical applications. We have found that a. under identical channel conditions the differential current is at least a factor 20 lower that the current flowing in each diode; b. the balanced photodiode is able to detect the presence or absence of water in the channel; c. the presence of fluorescein can be successful detected by our device without any need of optical filter of the excitation light.

These preliminary results demonstrate the successful integration of microfluidic network with a-Si:H photosensor for on-chip detection in biomedical applications.

8774-32, Session 7

Performances of amorphous silicon photodiodes integrated in chemiluminescence based -TAS

Domenico Caputo, Giampiero de Cesare, Massimo Nardini, Riccardo Scipinotti, Univ. degli Studi di Roma La Sapienza (Italy); Luisa S. Dolci, Mara Mirasoli, Aldo Roda, Univ. degli Studi di Bologna (Italy); Augusto Nascetti, Univ. degli Studi di Roma La Sapienza (Italy)

The performances of amorphous silicon (a-Si:H) photodiodes in the detection of chemiluminescent signal is caracterized in detail and

compared with commercial ultrasensitivie cooled CCD acquisition system as benchmark. The underlying idea is the development of stand-alone and compact ?-TAS that does not need bulky and expensive system for their operation as external focusing optics, excitation sources and detection devices.

The photosensors have been deposited by Plasma Enhanced Chemical Vapour Deposition (PECVD) on a glass substrate covered with a transparent conductive oxide (TCO) that acts as bottom electrode and window layer for the light impinging on the photodetector through the glass. The sensors are a-Si:H p-i-n photodiodes whose structure is p-type doped amorphous silicon carbide (a-SiC:H) / intrinsic a-Si:H / n-type doped a-Si:H with thickness equal to 10, 150 and 50 nm, respectively. A Cr/Al/Cr stacked structure vacuum evaporated on the a-Si:H diodes is the top contact. A PDMS layer with wells has been fabricated using an aluminum mold and then it has been bonded using an oxygen plasma pretreatment on the opposite side of the glass substrate with each well aligned with a photosensor.

In order to evaluate the on-chip detection performances and compare them with state-of-the-art conventional chemiluminescence detection an experimental setup has been implemented on an optical bench. The glass substrates have been put on a holder with the side with bonded PDMS wells facing-up and a CCD has been aligned above the structure focusing on the PDMS wells. In this way the CCD looks into the wells from above without any intermediate interface, while the a-Si:H photodiodes look in the wells from below through the glass substrate of the ?-TAS. The entire system has been enclosed in a dark-box. A flexible capillary connected to a syringe outside the dark-box has been used to fill the wells with test solutions.

The experiments have been performed by filling the wells with solutions containing different quantities of horseradish peroxidase enzyme (HRP) and a chemiluminescent cocktail. After each measurement the well has been emptied and rinsed with buffer solution and a blank control acquisition has been done. The photodiode signal has been acquired with a Keithley 236 Source Measure Unit for up to 40 minutes with 1 s sample time in order to follow the kinetic of the chemiluminescence signal. A very good linearity (regression factor around 0.998) is observed across the entire measurement range that starting from 50 fg spans over more than three orders of magnitude. The measured sensitivity is very close to 1 pA/pg or, referring to the HRP concentration, 4.4·103A/mol, with detection limit in the range of the amol limited by the kTC noise of the system. Experiments with target molecules immobilized on the functionalized glass surface have been also performed both in bulk and microfluidics regime proving the ability of the system to effectively detect chemiluminescent reactions and their kinetic. A very good agreement between CCD and the on-chip photodiode results has been achieved confirming the validity of the proposed integrated approach based on a-Si:H technology.

8774-20, Session PS

Mesoporous silica as the enzyme carrier for organophosphate detection and/or detoxification

Nina Francic, Aleksandra Lobnik, Univ. of Maribor (Slovenia)

In the past decade, interest in mesoporous materials has developed dramatically since they can be useful in a number of applications, including adsorption and sensor technology. Mesoporous materials are a class of nanostrustures with well-defined mesoscale (2–50 nm) pores, surface areas up to 1000 m2/g and large pore volumes (~1.0 mL/g). In general, ordered mesoporous materials are formed from solution by co-assembly and cross-linking of network-forming inorganic species (typically oxides) in the presence of structure-directing agents (SDAs) [1]. The SDAs are typically surfactants or blockcopolymers that self-organize into mesoscale (2–50 nm) structures, according to the solution composition and processing conditions used [2]. Owing to their structural properties and regular morphology, mesoporous silicas (MPS) are promising materials for applications in the immobilization processes or as supports for bulky bio-molecules, such as enzymes.

There is considerable interest in the enzymatic detection and detoxification of organophosphorous compounds (OPC), derivates in orthophosphoric and alkylphosphonic acids. These include pesticides widely used in agriculture which accumulate in the ground and water sources, as well as neurotoxic chemical warfare agents. In this respect, organophosphorous hydrolase - OPH (EC 3.1.8.1) - is the most important enzyme, as it catalyses the hydrolysis of very wide spectrum of neurotoxic organophosphorous compounds [3].

We report on the synthesis of mesoporous silica (MPS) particles and their potential use for immobilization of the enzyme hexahistidine tagged OPH (His6-OPH). Particle characterization points out a strong influence of the synthesis parameters (addition of ethyl acetate). BET results show a high specific surface area (300-450 m2/g) and an appropriate pore size distribution ranging from 10 to 40 nm. Immobilization of the enzyme His6-OPH, with the size of 72 kDa and isoelectric point (pI) of 8.5, was carried out in MPS particles of spherical morphology. Preliminary results indicate significant potential in use of encapsulated enzyme His6-OPH for the purpose of bio-sensing or in the detoxification processes of organophosphates.

References:

[1] Epping, JD; Chmelka, BF. Nucleation and growth of zeolites and inorganic mesoporous solids: molecular insight from magnetic resonance spectroscopy. Curr. Opin. Colloid Interface Sci., 2006, 11, 81-117.

[2] Athens, GA; Shayib, RM; Chmelka BF. Functionalization of mesostructured inorganic-organic and porous inorganic materials. Curr. Opin. Colloid Interface Sci., 2009, 14, 281-292.

[3] Efremenko EN, Sergeeva VS, Organophosphate hydrolase

8774-33, Session PS

Diagnostic of Epstein-Barr virus infection in clinical serum samples by SPR

Tomas Riedel, Cesar Rodriguez Emmenegger, Andrés de los Santos Pereira, Institute of Macromolecular Chemistry of the ASCR, v.v.i. (Czech Republic); Anna Bedajankova, VIDIA spol. s ro (Czech Republic); Eduard Brynda, Institute of Macromolecular Chemistry of the ASCR, v.v.i. (Czech Republic)

A biosensor for direct label-free detection of antibodies against the Epstein-Barr virus (EBV) in human serum was developed. The Epstein-Barr virus belongs to the family of herpes viruses and is one of the most common viruses, which attack human organism. It is recognized as a cause of infectious mononucleosis, lymphoproliferative disorders, and nasopharyngeal carcinoma. According to EBV-specific serological profiles for diagnoses, three different diagnoses were differentiated – 1) primary infection; 2) past infection; and 3) no infection. These diagnoses were based on the presence of antibodies against different EBV antigens, such as early antigen (EA), Epstein-Barr nuclear antigen (EBNA), and viral capside antigen (VCA).

An SPR chip was coated with poly(hydroxyoligoethylene glycol methacrylate) (poly(HOEGMA)) brush grown from its gold surface by surface-initiated atom transfer radical polymerization. A thickness of 30 nm of the brush layer was optimum to minimize the non-specific sensor response to the fouling from blood serum. Streptavidin was covalently bound to the brush and biotinylated oligonucleotides (ON) were attached. Serum albumin linked with the complementary oligonucleotides (CON) was conjugated with EA, EBNA, or VCA antigens and the conjugates were immobilized on the chip surface via hybridization between CON and the surface attached ON.

Clinical samples of blood sera were diluted with 1% serum albumin solution. The highest ratio of specific to non-specific responses measured in infected and reference healthy human sera, respectively, was achieved in 1% sera. An increase in the serum concentration led to an increase in the specific response accompanied by an even faster increase in the non-specific response. The specific response started to reach plateau at a 5% serum concentration.

Regeneration of the biosensor was possible by releasing the immobilized antigen conjugates if the temperature was increased to 45°C that was above the melting point of the complementary oligonucleotides ON and CON.

The SPR sensor was capable of recognizing different stages of EBV infection by evaluating the relative titer of the three respective antibodies detected directly in clinical serum samples.

Acknowledgement

This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic (grant No. CZ.1.07/2.3.00/30.0029).

8774-34, Session PS

Block copolymer brushes for antifouling functionalizable sensing surfaces

Andrés de los Santos Pereira, Cesar Rodriguez-Emmenegger, Institute of Macromolecular Chemistry of the ASCR, v.v.i. (Czech Republic); Aldo B. Alles, Univ. de la República (Uruguay); Eduard Brynda, Institute of Macromolecular Chemistry of the ASCR, v.v.i. (Czech Republic)

Biosensors designed to operate in complex biological media are usually subjected to interference caused by non-specific adsorption of medium components (fouling). Highly ordered polymer brushes grown by surface-initiated controlled polymerizations have shown superior performance as layers capable of preventing fouling. Furthermore, it is possible to attach bioreceptors to such brushes using the functional groups available on lateral chains of the polymer to achieve effective sensing surfaces. However, the procedure used for functional group activation and subsequent bioreceptor attachment can irreversibly alter the chemical and physical structure of the brush, thereby impairing fouling resistance. Additionally, there is partial loss of activity of the biomolecules upon immobilization on the surface, which decreases attainable sensor sensitivity.

In this work, we present an approach based on block copolymer brushes, grown on gold-coated chips for surface plasmon resonance spectroscopy, in order to overcome these limitations. Oligo(ethylene glycol) methyl ether methacrylate is chosen for the first block (10 – 20 nm) owing to its good antifouling performance and the fact that it is not altered during the functionalization step. For the second block, two alternatives are investigated: hydroxyl-functional oligo(ethylene glycol) methacrylate and carboxyl-functional zwitterionic carboxybetaine acrylamide. We show that antifouling performance is conserved to a much higher degree after immobilization of bioreceptors in the newly presented block copolymers compared to brushes of the corresponding homopolymer. Furthermore, we compare the immobilized amount and activity of bioreceptors using avidin-biotin interaction and an antibody-antigen pair through surface plasmon resonance.

Acknowledgment: This research was supported by the Czech Science Foundation (GACR) under Contract No P205/12/1702, P106/12/1451 and P205-12-G118.

8774-35, Session PS

A microfluidic platform with an optimal fluidic network for osteoarthritis diagnosis

Kangil Kim, Yoo Min Park, Hyun C. Yoon, Sang Sik Yang, Ajou Univ. (Korea, Republic of)

Osteoarthritis (OA) is one of the most common human diseases, and the occurrence of OA is likely to increase with the increase of population ages. The diagnosis of OA is based on patient-relevant measures, structural measures, and measurement of biomarkers that are released through joint metabolism. Traditionally, radiography or magnetic resonance imaging (MRI) is used to diagnose OA and predict its course. However, diagnostic imaging in OA provides only indirect information on pathology and treatment response. A sensing of OA based on the detection of biomarkers insignificantly improves the accuracy and sensitivity of diagnosis and reduces the cost compared with that of radiography or MRI.

In our former study, we proposed microfluidic platform to detect biomarker of OA (S. Y. Song etal., Anal. Biochem., 2012.). But the platform can detect only one biomarker because it has one microfluidic channel. In this report, we proposes microfluidic platform that can detect several biomarkers. The proposed platform has three layers. The bottom layer has gold patterns on a Si substrate for optical sensing. The middle layer and top layer were fabricated by polydimethysiloxane (PDMS) using soft-lithography. The middle layer has four channels connecting top layer to bottom layer. The top layer consists of one sample injection inlet, and four antibody injection inlets.

If the channels have equal widths andheights, the traveling times in the fluidic network from the first inlet to each detection chambers are different, because the channel lengths are different . To overcome this problem, a structural design of the fluidic network is required for the detection of OA. To this end, we designed an optimal microfluidic network using analogy between electric and hydraulic systems. And, the designed microfluidic network was confirmed by finite element model (FEM) analysis using COMSOL FEMLAB. To verify the efficiency of fabricated platform, the optical sensing test was performed to detect biomarker of OA using fluorescence microscope. We used cartilage oligomeric matrix protein (COMP) as biomarker because it reflects specific changes in joint tissues. The platform successfully detected various concentration of COMP (0, 100, 500, 1000 ng/?) at each chamber.

We proposed a microplatform for the detection biomarker of OA, and designed an optimal fluidic network in order to obtain equal sample volumes. The effectiveness of the microplatform was verifed computationally and experimentally.

8774-36, Session PS

Nanoplasmonic sensor for chemical measurements

Renato Iovine, Luigi La Spada, Lucio Vegni, Univ. degli Studi di Roma Tre (Italy)

In this contribution, plasmonic nanoparticles arranged in an array configuration for the detection of glycerol concentration in aqueous solution are presented.

Glycerol concentration measurements is crucial for several applications, such as biomedical engineering, biomicrofluidics, and lab-on-a-chip applications.

For this purpose, an LSPR (Localized Surface Plasmon Resonance) sensor, based on near field interaction of non spherical dielectric-filled metallic particles (nanoshell) deposited on a silica substrate, is proposed.

It is well known that LSPR phenomenon occurs when the electromagnetic field interacts with structures whose dimensions are smaller than the operative wavelength, and strongly depends on the inclusion geometry, its metallic electromagnetic properties and on the surrounding dielectric environment permittivity.

The detection of the presence of glycerol in aqueous solution by permittivity measurements is not simple, due to the fact that its refractive index shows small changes when different concentrations are considered.

In order to reveal such small differences an enhancement of the LSPR phenomenon is necessary. For this purpose, we propose to arrange nanoparticles in a planar array configuration with inter-particle distance much smaller than the incident wavelength. In this configuration the proposed non spherical nanoshell exhibits high sensitivity performances. Therefore, a uniform near electric field is obtain. It is remarked that the corresponding near electric field in the same volumes with solid-gold particles sensors result is a non uniform (dipolar) distribution. In this way a shift in the position of the sensor response is related to the different concentration of the material under test.

Numerical results, obtained through proper full-wave simulations, demonstrate that the sensor can be used for the recognition of glycerol and its concentration in a highly accurate and sensitive way.

8774-37, Session PS

Highly reproducible substrate for surface-enhanced Raman spectroscopy exploiting block copolymer self-assembly

Claudia Diletto, Univ. degli Studi di Napoli Federico II (Italy); Pasquale Morvillo, ENEA (Italy); Claudio De Rosa, Finizia Auriemma, Giulia Rusciano, Antonio Sasso, Univ. degli Studi di Napoli Federico II (Italy)

Block copolymers (BCPs), where chemically distinct macromolecules are joined together by covalent bonds, are subject of intensive worldwide research due to their potential applications in organic electronics. The excellent solubility in organic solvents makes this class of materials particularly attractive because thin films of BCPs can be deposited on a wide range of substrates through high-throughput, low-temperature processes using printing techniques yielding low-cost, flexible, and light-weight devices. The dissimilar blocks tend to segregate, due to their mutual repulsion, into distinct microdomains resulting in the spontaneous formation of periodic nanostructures with controllable dimensions and functionalities. The goal of this research activity is to develop innovative hybrid systems where a nanostructured block copolymer is selectively loaded with inorganic metal nanoparticles. Microdomains of BCPs nanostructures (sphere, cylinders or lamellar) that form spontaneously by self-assembly, may act as hosts for sequestering nanofillers of appropriate chemical affinity according to prefixed periodic geometries producing long-range order in the positioning of nanoparticles. The dispersion of nanoparticles in these structures allow the realization of hybrid nanocomposites of particular interest in microelectronic; in fact, the possibility to segregate the nanoparticles into one of the domains of a self-assembled BCP offers an attractive method to obtain a well-defined spatial arrangement of the nanocomposite. In the present work a polystyrene-poly(methylmethacrylate) amorphous block copolymer (PS-b-PMMA) was employed, with volume fraction of PS block selected in order to obtain a lamellar microphase separated morphology. In a first step, thin films of PS-b-PMMA was obtained by spin-coating at room temperature or drop casting after deposition of a slight excess toluene BCP solution on ITO (Indium Thin Oxide) substrate. The ITO glass substrate allows the obtainment of the desired vertical orientation of lamellae where the microdomains are disorderly dispersed[1]. In order to obtain nanostructures for the desired applications, it is necessary to have unidirectional long-range ordering and perfect orientation of microdomains. So, by applying an electric field in vacuum at a temperature above the glass transition temperature, these lamellae were perfectly aligned side by side realizing a periodic tridimensional structure with a long range order. Finally, an innovative procedure based on the selective deposition gold nanoparticles by evaporation and condensation was also used to obtain nanostructured hybrid systems. We demonstrate that metal atoms diffuse to the preferred vertically aligned domains forming nanoparticles with spatial selectivity on the surface of the film. These nanocomposites were investigated using surface-enhanced Raman Spectroscopy (SERS). Highly reproducible substrates for SERS applications were obtained exploiting self-assembly of BCP, selective inclusion of gold nanoparticles in the PS domains via evaporation and condensation and successive alignment of lamellar domains by application of electric fields. These substrates hold premise for single molecule detection.

[1] C. Diletto, P. Morvillo, R. Di Girolamo, F. Auriemma, C. De Rosa, Journal of Nanoscience and Nanotechnology, in press.

8774-38, Session PS

Optical biosensor based on cadmium sulfide-silver nanoplate hybrid structure

Shang Xin Lin, Huaqiao Univ. (China); Alex C. Wong, David S. Siu, Edwin Y. Pun, City Univ. of Hong Kong (Hong Kong, China)

Noble metal nanoparticles have recently shown great potential in cell imaging [1], photo-thermal therapy and nuclear damaging [2], which are the applications of surface plasmon resonance (SPR). Among the noble metal nanoparticles, gold (Au) or silver (Ag) nanoparticles are the top candidates for bio-sensing applications simply because of their non-toxicity and non-immunotoxicity to cells [3], good biocompatibility [4], and their SPR bands are within the visible to near infrared (NIR) region.

In the applications of SPRs in optical sensors, the modulation of active nanoparticles with noble metallic nanoparticles is a pre-requisite. To ensure compatibility with current demands on bio-sensing, cadmium chalocogenides (CdX, X = S, Se or Te) NPs have to be conjugated with Ag NPs. However, a number of technical issues exist, such as forward cationic ion exchange in mutual nanoparticles, conjugation efficiency, and occurrence of photoluminescence (PL) quenching in very close mutual distance (smaller than 5 nm). Thus, coupling CdX wth noble metallic NPs is one of the most active research works in surface plasmons [5, 6].

In this work, CdS-Ag nanoplate hybrid structure has been synthesized using a forward-reverse cation exchange. The morphology, crystallinity, and atomic composition of the CdS-Ag hybrid NPs were investigated using energy dispersive X-Ray spectroscopy and high resolution transmission electron spectroscopy, and the NPs were Cd2+-rich CdS NPs covalently bonded to the surfactant of the Ag nanoplates, and shows a 10-fold PL intensity enhancement at 670nm wavelength when compared with CdS NPs. The PL enhancement can be attributed to the matching of the emission bands of CdS and the tailor-made SPR bands provided by the Ag nanoplate. To demonstrate the application of the CdS-Ag NPs for cell imaging, the NPs were incubated with the cervical cancer cell line, HeLa. No apoptosis was observed under 20? magnifications by the cell morphology, indicating that the level of cytotoxicity of the hybrid NPs was negligible. Modified with target-specific bio-conjugates, this hybrid semiconductor-noble metal NPs would pave a way for the development of new bio-sensing materials, and confirms the practical applications of nanotechnologies in biosensors.

References

[1] R. Elghanian, J. J. Storhoff, R. C. Mucic, R. L. Letsinger, and C. A. Mirkin, Science 277, 1078 (1997).

[2] B. Kang, M. A. Mackey, and M. A. El-Sayed, J. Am. Chem. Soc. 132, 1517 (2010).

[3] M. A. Dobrovolskaia, and S. E. McNeil, Nat. Nanotechnol. 2, 469 (2007).

[4] Y. W. C. Cao, R. Jin, and C. A. Mirkin, Science 297, 1536 (2002).

[5] J. Zhang, Y. Tang, K. Lee, and M. Ouyang, Science, 327, 1634 (2010).

[6] J. Zhang, Y. Tang, K. Lee, and M. Ouyang, Nature, 466, 91 (2010).

8774-39, Session PS

Simulation of continuously logical ADC (CL ADC) of photocurrents as a basic cell of image processor and multichannel optical sensor systems

Vladimir G. Krasilenko, Vinnitsa Social Economy Institute (Ukraine); Aleksandr I. Nikolskyy, Alexander A. Lazarev, Vinnytsia National Technical Univ. (Ukraine); Oksana V. Krasilenko, National Aviation Univ. (Ukraine); Irina A. Krasilenko, Vinnitsa Social Economy Institute (Ukraine)

The paper considers results of design and modeling of continuously logical analog-to-digital converters (ADC) based on current mirrors for image processor and multichannel optical sensor systems with parallel inputs-outputs. For such multichannel serial-parallel analog-to-digital converters (SP ADC) it is needed base photoelectron cells, which are considered in paper. Its have a number of advantages: high speed and reliability, simplicity, small power consumption, high integration level for linear and matrix structures. We show design of the continuously logical ADC of photocurrents and its base digit cells (ABC) and its simulations. We consider CL ADC for Gray and binary codes. Each channel of the structure consists of several base digit cells (ABC) on 20-30 CMOS FETs and one photodiode. The supply voltage of the ABC is 1-3.3V, the range of an input photocurrent is 0.1 – 10uA, the transformation time is 30ns at 5-8 bit binary or Gray codes, power consumption is about 1mW. Such CL ADC opens new prospects for realization of linear and matrix image processor and photo-electronic structures with picture operands, which are necessary for neural networks, digital optoelectronic processors, neural-fuzzy controllers, and so forth.

8774-41, Session PS

The arms arrangement influence on the sensitivity of Mach–Zehnder fiber optic interferometer

Stanislav Kepak, Jakub Cubik, Jan Doricak, Vladimir Vasinek, Andrej Liner, Martin Papes, Petr Siska, Technical Univ. of Ostrava (Czech Republic)

Fiber-optic sensors based on phase shift measurements are one of the most sensitive sensors at all. In general they are capable to measure various phenomena, for example displacement, rotation, temperature,

acoustic pressure, liquid flow and level, strain etc. In our paper we have used interferometer configuration based on Mach-Zehnder principle with polarization maintaining components and narrowband DFB laser operating at a wavelength of 1550nm. As a detector an InGaAs PIN photodiode were used in this measurements. The electrical signal from the photodiode was amplified and fed into the measuring card. On the incoming signal the FFT was applied, which performs the transformation into the frequency domain and the results were further evaluated by software. In this configuration it is important to isolate the reference arm against measured phenomena and on the other hand to increase the sensitivity of the measuring arm to maximize phase shift induced by the measured phenomenon. The paper describes various arrangements of measuring arm in particular and their influence on the measurement sensitivity. The obtained frequency ranges are evaluated for different types of resonance cushions.

8774-42, Session PS

Rock massive temperature changes measurement with regard to thermal responses generated by a thermal response test device

Jan Latal, Jan Vitasek, Petr Koudelka, Petr Siska, Andrej Liner, Martin Papes, Vladimir Vasinek, Technical Univ. of Ostrava (Czech Republic)

In this article are presented results from application of fiber optical DTS system within long term research of temperature energy accumulation in Paskov rock massive. In this area was established special measuring station for that purpose, because rock massive in Paskov area has ideal properties for temperature changes measurement. The twelve geothermal boreholes were drilled during this research, which were then used for rock massive heating by Thermal Response Test device. With the help of DTS system was observed how the temperature distribution and penetration in between boreholes in rock massive is. Thanks to the DTS system we were able to determine the Thermal Response Test device heating power influence on the nearest monitoring boreholes.

8774-43, Session PS

Development of absorption fiber optic sensor for distributed measurement of ammonia gas

Jan Aubrecht, Ladislav Kalvoda, Czech Technical Univ. in Prague (Czech Republic)

During last decades, optical fibers have been used in various medical and industrial applications [1]. For instance, polymer clad silica optical fibers have been employed for development of different absorption optic fiber sensors of chemical gaseous analytes. Ammonia, as a harmful but widely industrially used gas dangerous even in low concentrations, sets demand for a high-efficiency fiber optic detection system of early warning. Our contribution deals with development of such system based on distributed fiber optic detection principle.

Important properties that have to characterized and optimized in order to get such system working relate to structural changes of the used opto-chemical absorption transducer (reagent) during its interaction with ammonia both in liquid phase and in solid polymer matrix. Selected organo-metallic complex transducers with different lengths of lateral aliphatic chains are studied with respect to several technologically important features, such as analysis of the type of central ions and their coordinative conditions to surrounding ligands, the effect of solvent type on solubility of the transducers and the long-term stability of the prepared reagents. Various methods are also tested in order to achieve an effective transducer immobilization into the polymer matrix creating the optical cladding of the fiber.

The chemical reaction of the reagent with ammonia based on ligand exchange process is accompanied by changes of VIS-NIR optical absorption influencing via evanescent field on the guided light intensity. This spectroscopic principle is combined with the optical time domain reflectometry (OTDR) method applied for spatial and temporal resolution along the whole active fiber length [2]. Spectral measurements performed with aid of a fiber optic grating-based analyzer are used to characterize the reaction kinetics.

The setup for OTDR measurements consists of a commercially available OTDR unit operating at 850 nm and a modified optical fiber placed in 3 separated testing chambers substituting a distributed system. The sensing system function is tested using ammonia/nitrogen mixtures of various ammonia concentrations (1 – 10000 ppm) prepared by mass flow controllers and injected into the testing chambers.

Experimental results show that the selected transducers provide properties suitable for practical application and the prepared PCS optical fibers can be used for detection of gaseous ammonia at low concentrations. The used OTDR method is proved to provide the spatial resolution sufficient for practical location of ammonia leaks.

The research has been supported by the grant MSM6840770040 of the Ministry of Education, Youth and Sports of the Czech Republic and the grant SGS10/296/OHK4/3T/14 of the Czech Technical University in Prague.

Reference:

[1] L. Kalvoda, J. Aubrecht, P.Levinsky, Development of Distributed Fiber Optic Sensor of Ammonia

Gas. In: A. Fekete et al. (Eds.), Ammonia: Structure, Biosynthesis and Functions, 2011.

[2] J. Aubrecht J. L., Kalvoda L. P., Levinsky P., Development of distributed fiber optic sensor of ammonia gas, XI Conference on Optical Chemical Sensors and Biosensors, 2012.

8774-44, Session PS

Usage of Raman DTS for wooden material analysis

Vladimir Vasinek, Jan Latal, Petr Koudelka, Andrej Liner, Martin Papes, Vladimira Rasnerova, Technical Univ. of Ostrava (Czech Republic)

The contribution deals with usage of Raman DTS for thermal transmittance monitoring and moisture monitoring in wooden buildings and constructions. Temperature measurement and thermal transmittance is notable for an analysis of moisture distribution inside of wooden girders that are the basic construction parts of wooden buildings during their seasoning and sanitation. In this contribution the results from measurements within real wooden objects will be presented and these results will be compared with laboratory experiments under controlled conditions. For wood sanitation two types of heating are used – flow of hot air and microwave heating. A multimode fiber 62,5/125 in primary coating is applied for measurements, this fiber is putted on the inside and outside surface of wooden construction. Here the fiber meanders are created inside of wooden girders with spacing of 1 cm. Optical fibers are laid in two mutual perpendicular cuts with usage of temperature resolution better than 0,05oC. The measured length of wooden girder is 1,4 m for unambiguously temperature specification inside the girder and its thermal transmittance. The temperature maps of various types of wooden girders are the results of analysis. Different multimode fibers with particular fiber coatings are included in the analysis.

These measurements have been provided with Sentinel DTS and they are parts of a wide set DTS application for building industry. We are trying to specify the influence of fiber bending on temperature sensitivity, how to join measuring fiber to transporting fiber, critical length of both fibers and many others. Raman DTS can replace large number of thermometers and provide continuous information about temperature distribution.

8774-45, Session PS

Highly sensitive BOTDR demodulation method based on slow-light MZI

Yong Zhao, Bo Han, Qi Wang, Chuan Qin, Northeastern Univ. (China)

When Mach-Zehnder Interferometer (MZI) is utilized in BOTDR,

the sensitivity of BOTDR has to be very low in order to reduce the power of noise light. Although a double-pass MZI was proposed to demodulate the signals, the sensitivity of MZI based BOTDR was still very low. In this paper, to improve the sensitivity of BOTDR based on MZI demodulation method, a novel demodulation structure and principle were proposed by using slow-light MZI. The slow-light MZI was realized by introducing a Fiber Grating (FG) in one of MZI arms. The FG was utilized not only as a filter to reduce the noise caused by Fresnel reflection and Rayleigh scattering, but also as the slow-light medium to improve the sensitivity of MZI used in BOTDR. The lower the transmission of FG corresponding to noise light wavelength could be, the more the noise power will be reduced. And the higher the group index could be, the higher the sensitivity of MZI could be improved. To analyze the characteristics of FG and find out suitable FG structure, a model was built based on Transmission Matrix Method (TMM) to calculate various spectra of FG with different kinds of structures. Firstly, both uniform FG and Gaussian FG were modeled to calculate the transmission spectra and group index spectra. It was found that although uniform FG could effectively reduce the noise power, the group index in it was not improved significantly. And Gaussian FG could realize more obvious slow light than uniform FG, which could mean higher sensitivity of BOTDR, but it could not effectively reduce noise power. So, none of uniform FG and Gaussian FG was satisfactory. Then, to further improve the sensing characteristic of BOTDR based on MZI, the Inverse-Gaussian Fiber Grating (IGFG) was utilized, which, to our knowledge, was proposed for the first time. IGFG was proposed to realize significant slow light on long-wavelength side lobe, which could not only reduce noise power effectively, but also improve the sensitivity of BOTDR. To proof that the novel Inverse-Gaussian index profile could improve group index, the group index spectra of IGFGs with same average index but different full width at half maximum (FWHM) indexes were modeled and compared with one of uniform FG. The numerical results showed that Inverse-Gaussian index profile could realize large group index on long-wavelength side lobe and a shorter FWHM would lead to a higher group index. By calculating the transmission of FG corresponding to the noise wavelength and the sensitivities of BOTDR based on slow-light MZI demodulation method, it was found that as the transmission corresponding to noise wavelength could be zero, and the power of noise light could be reduced effectively due to the introducing of IGFG. What' s more, the phase and relative output power sensitivities of BOTDR demodulation could be improved to almost 50 times as large as the ones based on the double-pass MZI. Besides, the sensitivity of BOTDR distributed sensor could also be improved.

8774-46, Session PS

Assay for optical determination of biogenic amines using microtiter plates

Polona Nedeljko, Matejka Turel, Institute for Environmental Protection and Sensors, Ltd. (Slovenia); Aleksandra Lobnik, Institute for Environmental Protection and Sensors, Ltd. (Slovenia) and Univ. of Maribor (Slovenia)

Biogenic amines (BAs) are biologically active nitrogenous compounds, of low molecular weight, which are formed or metabolized in the cells of living organisms [1]. Catecholamines are group of BAs and play an important role in clinical analysis, as important neurotransmitters. They are responsible for communication between the nerve cells, and for various important functions in the body, such as regulation of stress response, psychomotor activity, emotional processes, learning, sleep and memory [2]. The determination of catecholamines and their metabolites levels in plasma and urine is especially relevant for the clinical diagnosis, particulary in tumors cases.

Due to the increasing awareness of the toxicological effects of catecholamines found in food, as well as their important metabolic functions in cells of living organisms, there is a need to develop rapid, simple, and cheap methods for their determination. The most important methods for the determination of catecholamines are chromatographic methods [3]. These methods are usually difficult, time consuming, require time intensive sample pretreatment, expensive analytical instrumentation and a skilled person. The aim of the research was to develop a fast and sensitive optical chemical sensing scheme for the detection of clinicalls important BAs, such as catecholamines. An indicator molecule that forms a fluorescent complex with BAs was chosen for this purpose and the assay was carried out in microtiter plates. The sensing system was optimized according to pH, response time, dynamic range, limit of detection, complex stability, sensitivity, indicator concentration and interferences.

8774-47, Session PS

Analysis of fano-line shapes from agile resonant waveguide grating sensors using correlation techniques

Kristelle Bougot-Robin, Weijia Wen, Hong Kong Univ. of Science and Technology (Hong Kong, China); Henri Benisty, Lab. Charles Fabry (France)

Resonant profile shift resulting from a change of refractive index (from refractive index of the liquids close to the chip or the effective thickness of an immobilized biological layer on the chip surface) is frequently used to perform label-free sensing. The asymmetric Fano resonance lineshape, resulting from interference between background and a resonant scattering, is archetypal signal in resonant based sensing. Lineshapes are sometimes sampled at discretized "detuning" values to relax instrumental demands, the highest reflectivity element giving a coarse resonance estimate. A finer extraction, needed to gain in sensor sensitivity, is obtained either by fitting data to known models or, as presented here, using a correlation approach, correlating the sensed signal to a zero-shifted reference signal. From its design flexibility advantages (optical configuration and light-matter interaction optimization depending of the analytes to detect), we choose to use dielectric resonant waveguide grating (RWG) structures. We demonstrate experimentally and theoretically the superior merits of correlation against Gaussian and Lorentzian shape fitting, featuring high immunity to several parasitic contributions (noise, distortions). Our findings are illustrated with silicon nitride on glass RWGs designed for near normal incidence imaging and operated at visible wavelengths. We recently demonstrated that direct imaging multi-assay RWGs sensing may be rendered more robust using "chirped" RWG chips. The scheme circumvents the classical but demanding spectral or angular scans: instead of varying angle or wavelength through fragile moving parts or special optics, a RWG structure parameter is varied. Considering sensitivity and multiplex imaging aspects, we choose to vary the filling factor, and make sensing "tracks" composed of several RWG "micropad" units of period P=450 nm with slowly varying groove widths. Micropads have neighboring resonant conditions, and a spatial Fano lineshape profile is measured in filtered condition, here with l=545 nm, at an incidence angle q~18? and in TM polarisation. Extracting the resonance location using plain images of these "pixelated" Fano profiles allow multiplex refractive index based sensing. For our filling factor variation of Df=0.0089 (variation of the groove width by step of 4 nm), an improvement over the "best-pixel" maximum position tracking by more than 2 orders of magnitude is obtained and provides down to 2?10-5 RIU sensitivity. This corresponds to a density of ~20 pg/mm2 for biomolecules detection, suitable for real-time hybridization studies. For imaging in a MxN array format, several "tracks" may be disposed on the chip, offering in a single picture few tens or even hundreds of tracks, fitting typical needs for multiplex sensing. Our chip based configuration allows to benefit from advantages of dielectric guided wave biochips without the need of costly hyperspectral or angular scan instrumentation. The current success of surface plasmon imaging techniques suggests that our work could leverage an untapped potential to routinely extend such techniques in a convenient and sturdy optical configuration. Together with highly accurate fitting demonstration through correlation analysis, our scheme based on a "Peak-tracking chip" demonstrates a new technique for label-free bioarray imaging or refractive index sensing with a simpler imaging set-up that maintains high performance with cheap lenses.

8774-49, Session PS

Vibration sensor using fiber optic coupler

Kishore Putha, Dinakar Dantala, Vengalrao Pachava, Srimannarayana Kamineni, National Institute of Technology, Warangal (India)

A simple fiber optic vibration sensor is designed using 2x2 coupler based on the principle of reflection intensity modulation. An LED

(650 nm) and high sensitivity photodarlington detector (PD) housed in a connector less package are used as a source and to detect the modulated light intensity corresponds to the vibration of the object. A simple detection circuit is designed to convert the modulated light intensity into its equivalent voltage signal and NI-DAQ with LabVIEW software is used to record the time domain signal (TDS) of the object which is vibrating. By using Fast Fourier transform (FFT), the frequency and amplitude of vibrations are measured from TDS. The 2x2 coupler is made from the multimode PMMA fiber of core/cladding diameters about 980/1000 μm and 100cm in length with splitting ratio of 80:20. All the four parts of the coupler are used for the vibration detection. The LED light is coupled to the port A, the coupled light is split (80:20) and a part of light is transmitted through the port C acts a sensing probe and other part is directed to PD1 through port D used as a reference. The light from port C is projects onto the vibrating object then the modulated reflected light is recoupled into the same fiber (port C) and directed to incident on the PD2 through port B.

The rational output of PD1 and PD2 is used to avoid the effect of source signal power fluctuations and fiber bending loss. A suitable calibration has taken place from the displacement characteristic of the sensor and the high sensitive linear region about 1mm is considered for vibration measurement. The experimental results show that the sensor is capable to measure the frequency of the object up to 3000 Hz with ~1μm resolution of vibration amplitude over a range of 0-1mm. In comparison with dual-fiber and bifurcated-bundle fiber, it eliminates the dark region and front slope which facilitates the easy alignment. The simple design, non-contact measurement, high degree of sensitivity, economical and with advantages of optical fiber are attractive attributes of the designed sensor that lend support to real time monitoring and embedded applications.

8774-50, Session PS

Spectral interferometry-based surface plasmon resonance sensing of liquid analyte refractive index change

Dalibor Ciprian, Petr Hlubina, Jirí Lukásek, Technical Univ. of Ostrava (Czech Republic)

Theoretical study of a polarimetric setup intended to measure the refractive index change of a liquid analyte is presented. The detection scheme is based on the excitation of surface plasmon resonance in Kretschmann configuration combined with spectral interferometry. The principle of the method is to observe the spectral interference fringes as a result of mixing of two orthogonal linearly polarized waves with an analyzer. The waves are reflected from the base of a coupling prism covered by a thin metal layer used for generation of surface plasmon waves. The polarimetric setup is the modified version of previously proposed scheme [1] successfully used for ellipsometric phase measurement applied to thin film structure. It consists of a linear polarizer, a birefringent crystal, a coupling prism and a linear analyzer. The equilateral coupling prism consisting of SF10 glass was considered, the base of the prism covered by a 44 nm thick golden layer. The collimated light beam from white light source passes through the linear polarizer whose axis is oriented in such a way that two linearly polarized waves with equal amplitudes are excited on its output. Then the waves undergo attenuated total reflection at the prism interface with the gold layer. The attenuated total reflection serves for the excitation of surface plasmon resonance. One of the waves, perpendicularly polarized with respect to the prism base (p-polarized wave), is influenced by the surface plasmon resonance excited on the outer boundary of metal layer in contact with the analyte but the other (s-polarized wave) is not influenced. After the reflection both waves pass through the analyzer whose axis is oriented to obtain optimal polarization mixing. The output optical field is then analyzed by a spectrometer. The phase change of resulting interference spectrum contains the information about the refractive index change of investigated analyte. The detection of such a change is based on the processing of spectral phase. In order to obtain the spectral phase the spectrum has to be in the form of spectral fringes. To generate the interference spectrum (spectral fringes), a birefringent crystal serves as a delay line, introducing the phase shift between the mentioned linearly polarized waves. In our case, the birefringent quartz crystal with thickness of 6 mm is considered. The phase is then reconstructed from the spectral fringes by means of windowed Fourier transform. The shift of reconstructed phase curve is related to the analyte refractive index change. The model computation is performed in the frame of thin-film optics and the dispersion properties of all included materials are taken into account. The described polarimetric setup is much simpler then the surface plasmon resonance sensing setup working on similar principle, which is described in [2]. Here the measurement is performed using a Michelson interferometer with two surface plasmon resonance coupling prisms, where one is placed into testing arm and the other one into reference arm. Such a design requires a more complicated adjusting and alignment procedure.

[1] Petr Hlubina, Dalibor Ciprian and Jirí Lu?á?ek, Spectral interferometric technique to measure the ellipsometric phase of a thin-film structure, 2009, Opt. Letters, v. 34, p. 2661

[2] Siu Pang Ng, Chi Man, Lawrence Wu, Shu Yuen Wu and Ho Pui Ho, White-light spectral interferometry for surface plasmon resonance sensing applications, Opt. Express, 2011, v. 19, p. 4521

8774-51, Session PS

Reflectance of various porous silicon structures at molecular adsorption

Igor Iatsunskyi, Valentin Smyntyna, Nykolai Pavlenko, Olga Kanevska, Valera Myndrul, Odessa I.I. Mechnikov National Univ. (Ukraine)

Porous silicon (PS) can be used as material in sensing applications and in the detection of vapors, liquids, and biochemical molecules. PS exhibits a great potential in optical sensor applications due to the possibility to change its reflectance index and luminescence properties after adsorption of molecules. The sensitivity of an optical sensor depends on the adsorption properties of the measured substances and the interaction of the specific analyte with the porous silicon, which can be adjusted and improved by proper fabrication parameters. Such parameters as pore size, pore distribution and porosity can significantly effect on adsorption properties as well.

Recently, a new method for porous silicon production, termed metal-assisted chemical etching, has been developed, which is relatively simple compared to the electrochemical method. The method does not need an external bias and enables a formation of uniform PS layers more rapidly than the conventional stain etching method. Thin metallic films or particles (Au, Pt, Al, Pd, etc.) are generally deposited directly on a silicon surface prior to immersion in an etchant composed of HF and an oxidizing agent.

An impact of morphology on photoluminescence and reflectance of porous silicon is analyzed using the numerical simulation and supported experiment under gas adsorption. Depending on the metal-assisted chemical etching conditions the macro- micro – or nanoporous structures could be formed. It was investigated the photoluminescence properties of porous silicon layers in presence of gas molecules (NH3, O2, CO2 etc.). It was found that luminescence properties of the PS are very sensitive to the surface properties of PS and it might be enhanced by surface modification. Ab initio model for PL after gas molecular adsorption was proposed. The reflectance spectra of various porous structures after molecular adsorption was investigated.

8774-52, Session PS

Study and design of an optode for pH measurement

Denis M. G. Doizi, Mathias Fages, Guy Deniau, CEA (France)

Nowadays, the development of industrial processes which focus on sustainable development, optimization of resources and minimization of pollution needs to create new analytical techniques to perform on-line measurements in the heart of the process. Benefits related to this development are risks reduction - by avoiding the steps of sampling -, the improvement of the quality of the products - by a real-time control of the process - and the cost reduction - through the development of inexpensive sensors.

A new pH sensor, using a patented process to graft a dye on an optical fiber, thus creating a system called “optode”, is currently under development in the laboratory. The absorption spectrum of the dye varies with the pH, so, after calibration using standard buffer solutions,

the pH of the medium is simply measured by analyzing this absorption spectrum, provided that the pH is within the field of measurement of the optode.

This type of sensor based on optical fibers has already been studied, but, until nowadays, there have always been difficult issues as concerns the stability of the dye and the response time of the measurement. Effectively, in most of the previous studies, the dye is dropped off on the fiber using physical entrapment or electrostatic attraction. However, the lifetime of the optode is limited due to the desorption of the dye, which causes two problems: the progressive decrease of the strength of the optical signal and the contamination of the medium.

The process we are using to graft the dye on the fiber, called GraftFastTM, uses diazonium salts intermediates to covalently bond the dye to the fiber. This technique should provide better stability of the optode, increasing the lifetime of the optode and protecting the medium from contamination, and fast time response. Moreover, the GraftFastTM process is very simple and fast, providing us with a really effective method to produce a low-cost optode.

Such an optode could have different applications, including environmental monitoring, process control (e.g. in nuclear waste reprocessing), or the control of mechanical properties of the concrete (which can sometimes be linked with the surrounding pH).

8774-53, Session PS

Hybrid interfaces for a new class of optical biosensors

Luca De Stefano, Monica Terracciano, Jane Politi, Alessandro Caliò, Ilaria Rea, Ivo Redina, Istituto per la Microelettronica e Microsistemi (Italy); Paola Giardina, University of Naples “Federico II” (Italy)

A new family of hybrid organic-inorganic devices can be designed and realized by using biomolecules extracted by natural organisms. DNA single strands, proteins, and enzymes are by far used in many successful applications, mainly in the diagnostic and monitoring fields. Beyond biosensors, biomacromolecules can be directly used to change physical and chemical properties of organic materials. In this communications, we report our newest results about the modification of silicon related surface by using the siloxanes, proteins and other biomolecules for diagnostic applications.

8774-54, Session PS

Detection and localization of building insulation faults using optical fiber DTS system

Martin Papes, Andrej Liner, Petr Koudelka, Petr Siska, Jakub Cubik, Stanislav Kepak, Vladimir Vasinek, Technical Univ. of Ostrava (Czech Republic)

Nowadays the trends in the construction industry are changing at an incredible speed. The new technologies are still emerging on the market. Sphere of building insulation is not an exception as well. One of the major problems in building insulation is usually its failure, whether caused by unwanted mechanical intervention or improper installation. The localization of these faults is quite difficult, often impossible without large intervention into the construction. As a proper solution for this problem might be utilization of Optical-Fiber DTS system based on stimulated Raman scattering. Used DTS system is primary designed for continuous measurement of the temperature along the optical fiber. This system is using standard optical fiber as a sensor, which brings several advantages in its application. First, the optical fiber is relatively inexpensive, which allows to cover a quite large area for a small cost. The other main advantages of the optical fiber are electromagnetic resistance, small size, safety operation in inflammable or explosive area, easy installation, etc. This article is dealing with the detection and localization of building insulation faults using mentioned system.

8774-55, Session PS

Electromagnetic study of magneto-optic surface plasmon resonance effects for biosensing applications

Abdul Aleem Jamali, Sebastian Kübler, Nicolas Müglich, Bernd Witzigmann, Univ. Kassel (Germany); Arno Ehresmann, Univ. of Kassel (Germany)

Biosensors are gaining interest in scientific research because of its wide variety of applications. Surface plasmon resonance (SPR) based biosensors are the most common platform for label free biomolecular interaction analysis. Recently it has been demonstrated that the sensitivity against refractive index changes of the dielectric media can be enhanced by a combined measurement of the transversal magneto-optic Kerr effect (TMOKE) and SPR [1,2]. In this paper, we present simulations of a magneto-optic SPR (MOSPR) biosensor by using a three-dimensional finite integration technique (FIT). In addition, experimental structures have been realized for comparison. As a benchmark, we apply the FIT as implemented in CST Microwave Studio (MWS) to simulate the SPR curve of a 50 nm Au layer. It is then compared to the SPR curve computed analytically. The reflectivity curve shows an excellent agreement between the simulation and analytical solution.

In the past the SPR biosensors have been modeled with the FIT, here, we extend this technique by incorporating anisotropic materials such as cobalt or Fe for an MOSPR sensor. The MOSPR biosensor uses the properties of surface plasmon polaritons (SPPs) and transverse magneto-optic Kerr effect (TMOKE) simultaneously in the presence of an external magnetic field [1]. We study the magneto-optical activity on the Au/Co/Au trilayer structures with opposite magnetization. The trilayer system is optimized for achieving high sensitivity. The magneto-optic activity strongly depends on the metallic layer thicknesses and the refractive index of the dielectric [2,3].

We compare experimental and simulation results of MOSPR biosensor in Kretschmann configuration with air as a dielectric, and get good agreement. The simulation exhibits the electric and magnetic field distributions along the trilayer system. Based on the comparison to the experiment, we investigate the sensitivity of an MOSPR biosensor by changing the refractive index of the adjacent dielectric material from 1.33 to 1.40. Furthermore, we compare the performance of an MOSPR sensor to a SPR one. As an outlook, the general three-dimensional FIT is applied to nanostructured MOSPR sensors, which utilize a photonic crystal effect.

[1 D. Regatos, D. Farina, A. Cebollada, B. Sepulveda, G. Armelles, and L.M. Lechunga; J. Appl. Phys., 108, 054502, 2010.

[2] K. Kämpf, S. Kübler, F. W. Herberg, and A. Ehresmann; J. Appl. Phys., 112, 034505, 2012.

[3] C. Clavero, K.Yang, J.R. Skuza, and R.A. Lukaszew; Optics Express (7743-7752), Vol.18, No. 8, 2010.

8774-56, Session PS

Compact and cost effective instrument for detecting drug precursors in different environments based on fluorescence polarization

Juan C. Antolín Urbaneja, Iñigo Eguizabal, Nerea Briz, Alberto Dominguez, Patxi Estensoro, TECNALIA Research & Innovation (Spain); Alberto Secchi, SELEX Sistemi Integrati S.p.A. (Italy); Antonio Varriale, Consiglio Nazionale delle Ricerche (Italy); Stefano Di Giovanni, Laboratory for Molecular Sensing, IBP-CNR (Italy); Sabato D’Auria, Consiglio Nazionale delle Ricerche (Italy)

Several techniques for detecting chemical drug precursors have been developed in the last decades. Most of them are able to identify specific molecules at very low concentration under lab conditions. Other commercial devices are able to detect a fixed number and type of target substances based on a single detection technique providing an absence of flexibility respect to target compounds. The construction

of detection systems defined as compact, easy to use and providing screening over a large number of compounds and discriminating them with low false alarm rate and high probability of detection is still an open concern. Under CUSTOM project, funded by the European Commission within the FP7, a stand-alone portable sensing device based on multiple techniques is being developed. One of these techniques is based on the LED induced fluorescence polarization to detect ephedrine and Benzyl Methyl Keton (BMK) as a first approach. This technique is highly selective with respect to the target compounds due to the generation of properly engineered fluorescent proteins which are able to bind the target analytes, as it happens in an 'immune-type reaction'.

This paper deals with the advances in the design, construction and validation of the physical prototype of the LED induced fluorescence sensor to detect the selected target analytes. This sensor includes an analysis module based on a high performance LED and PMT detector, the sample interface and handling module which comprises a fluidic system and some printed circuit boards. All the subsystems are controlled by a tiny microcontroller embedded in a specific designed printed circuit board to acquire some process signals and to control the subsystems in order to perform measurements based on differences between light signals from the sample. All the modules are fixed in a simple structure, given an appearance of unique module (167mmx193mmx228mm) with the capability of working as a stand- alone application but with the finality to send the results to the supervisor controller in order to cross the results with the other technique.

8774-57, Session PS

Tubular optical waveguide particle plasmon resonance biosensor for multiplex real-time and label-free detection

Chen-Han Huang, Hsing-Ying Lin, National Cheng Kung Univ. (Taiwan); Lai-Kwan Chau, National Chung Cheng Univ. (Taiwan)

We propose a label-free evanescent field absorption sensor, namely, tubular optical waveguide particle plasmon resonance (TW-PPR) sensor, relied on an unsophisticated light intensity interrogation scheme for biochemical analyte detections. The sensor retains the desirable feature of conventional surface plasmon resonance (SPR) reflectometry, the ability to monitor the kinetics of biomolecular interactions in real time without a label, but which has other important advantages: the sensor is easy to fabricate and simple to implement. In addition, it possesses the superiority of itself being a plasmonic waveguide, sensing channel, and sample container as well. The necessity of employing a microfluidic chip for sample fluid holding can be circumvented. The TW-PPR sensor can be large amount duplicated to enable higher-throughput monitoring of biomolecular interactions in a compact multichannel 2D array-based sensing format, which is comparatively tough accomplished by multiple fiber-optic particle plasmon resonance (FO-PPR) sensors since the increased complexity of microfluidic chip design should be considered in advance. The TW-PPR sensor is fabricated by chemically immobilizing a self-assembled monolayer (SAM) of gold nanoparticles (AuNPs) on the inner wall surface of a glass vial, and then modifying functional molecules which can specifically probe analytes on the AuNP surface. The sensing principle of the TW-PPR sensor relies on measuring the changes of transmission optical intensity from the nanoparticle-immobilized optical waveguide in response to the interfaced dielectric constant variation, for which the plasmon induced evanescent field around nanoparticles are sensitive to the interaction between an analyte and functionalized probes. This evanescent field penetrates into the surrounding medium in the vicinity of nanoparticles and interacts with analytes. Since light propagates in the tubular waveguide by virtue of consecutive total internal reflections (TIRs), the superposition of each localized evanescent field forms a continuous evanescent field plane at the waveguide surface immediately adjacent to the region occupied by a propagating mode. Hence, the optical signal variation of absorbance of AuNP film can be strongly enhanced by the tubular optical waveguide evanescent field absorption sensing scheme. Furthermore, a compact multichannel TW-PPR sensing platform is developed (currently seven channels for parallelized measurements plus one channel for blank reference) for the higher-throughput determination of an analyte. The total detection time only takes 12 to 20 minutes. As a device for direct sampling, the sample injection can be accomplished by using a multichannel pipette or several syringes, and this is considered to be particularly convenient in the cases of blood and biological fluids. The sensor resolution is estimated to be 2.6x10^-6 RIU in measuring solutions of various refractive indices (RIs). Additionally, the multichannel TW-PPR sensing system can perform independent measurements simultaneously and its limit of detection (LOD) of anti-DNP antibody and streptavidin separately measured by DNP-functionalized and biotin-functionalized TW-PPR microchambers is demonstrated to be 1.21x10^-10 and 2.27x10^-10 g/ml, respectively. Accurate determinations of these molecules with known concentrations spiked in artificial urine are examined and the sensor responses give excellent correlation with results demonstrated in standard buffer examinations, supporting the utility of the device for analyte screening in more complex media.

8774-58, Session PS

Comparison of optical and electrical investigations of meat ageing

Elena Prokopyeva, Pavel Tomanek, Brno Univ. of Technology (Czech Republic); Lucie Kocová, Tomas Palai-Dany, Zdenek Balík, Pavel Skarvada, Lubomír Grmela, Brno Univ of Technology (Czech Republic)

Different methods, such as ultrasonic, electromagnetic, optical and electrical methods can be principally used for meat aging detection. Thus the objective of this work is to assess the feasibility of impedance measurements for meat aging detection and their comparison with optical polarization measurement of backscattered light.

Due to the fact that muscles are electrically and optically anisotropic media, meaning that muscle and thus meat exhibit changes in electrical and optical properties according to the direction of the electrical and optical fields in the sample. After rigor mortis, the electrical impedance of meat decreases linearly with the mechanical resistance of muscle fibers, and electrical anisotropy is a better predictor of muscle fiber strength than impedance alone. Due to the optical chirality of the meat, the angles of back-scattered polarization plane changes with time.

The pork chop slices were used for their relative homogeneity. An investigation was carried out for the detection of the age of unpacked slices exposed directly to the air, and other packed in polyethylene bags. The meat samples were stored at 5 °C for a period of one week. Each measuring day one slice of each type of conservation was used.

The electrical method is a promising method due to the possibility of getting many information and realizing measurement systems with low costs and with in short measurement times.

We continue to discover new knowledge to understand light interactions with aging muscle structure.

The overall goal of this project is to determine the relationships between optical scattering characteristics, electrical anisotropy in aging-related tissue structural properties with the idea that these findings may be used alone, or in conjunction with other predictors, to develop a computer vision system for predicting meat freshness.

8774-59, Session PS

A new hyperspectral imaging based device for quality control in plastic recycling

Silvia Serranti, Giuseppe Bonifazi, Univ. degli Studi di Roma La Sapienza (Italy); Alberto Dall'Ava, DV SRL (Italy)

The quality control of contamination level in the recycled plastics stream has been identified as an important key factor for increasing the value of the recycled material by both plastic recycling and compounder industries. Existing quality control methods for the detection of both plastics and non-plastics contaminants in the plastic waste streams at different stages of the industrial process (e.g. feed, intermediate and final products) are currently based on the manual collection from the stream of a sample and on the subsequent off-line laboratory analyses. The results of such analyses are usually available after some hours, or sometimes even some days, after the material has been processed. The laboratory analyses are time-consuming and

expensive (both in terms of equipment cost and their maintenance and of labour cost).Therefore, a fast on-line assessment to monitor the plastic waste feed streams and to characterize the composition of the different plastic products, is fundamental to increase the value of secondary plastics. The paper is finalized to describe and evaluate the development of an HSI-based device and of the related software architectures and processing algorithms for quality assessment of plastics in recycling plants, with particular reference to polyolefins (PO).

The proposed hardware (HW) architecture takes into account the possibility, not only to perform static, but also dynamic analysis, that is the possibility to carry out the analysis on-line. HW architecture has thus to mimic the typical characteristics of a quality control and/or sorting unit, that is a device able to perform a continuous monitoring of a moving flow stream composed of particles or materials (e.g. plastic wastes). The software (SW) procedures utilized to handle the devices, to acquire and to analyze the spectra embes several features, that is: i) the possibility to perform a full spectral sensor data and acquired parameters control, ii) the conveyor belt control and synchronization with spectral data acquisition, iii) the collected reflectance data processing and analysis, iii) the possibility to realize a complete hyperspectral image reconstruction, as well as the automatic and/or interactive plot of the spectral data, iv) the possibility to utilize and apply several multi-feature classifications logics to identify and define the classes of features to utilize for particulate solids characterization, inspection and quality control and vi) data exporting.

NIR-HSI sensing devices coupled with multivariate data analysis methods was demonstrated as an objective, rapid and non-destructive technique that can be used for on-line quality and process control in the recycling process of POs.. In particular, the adoption of the previous mentioned HD&SW integrated architectures can provide a solution to one of the major problems of the recycling industry, which is the lack of an accurate quality certification of materials obtained by recycling processes. These results could therefore assist in developing strategies to certify the composition of recycled PO products.

8774-60, Session PS

Quality control in the recycling stream of PVC from window frames by hyperspectral imaging

Valentina Luciani, Silvia Serranti, Giuseppe Bonifazi, Univ. degli Studi di Roma La Sapienza (Italy); Francesco Di Maio, Technische Univ. Delft (Netherlands); Peter C. Rem, Delft Univ. of Technology (Netherlands)

Polyvinyl chloride (PVC) is one of the most commonly used thermoplastic materials in respect to the worldwide polymer consumption. PVC is mainly used in the building and construction sector, products such as pipes, window frames, cable insulation, floors, coverings, roofing sheets, etc. are realised utilising this material. In recent years, the problem of PVC waste disposal gained increasing importance in the public discussion. The quantity of used PVC items entering the waste stream is gradually increased as progressively greater numbers of PVC products approach to the end of their useful economic lives. For example, considering that an average PVC window has a life span of 30-40 years and the large scale consumption of PVC started in the 1970s, a significant increase in PVC waste generation is expected in the near future. The quality of the recycled PVC depends on the characteristics of the recycling process and the quality of the input waste. Not all PVC-containing waste streams have the same economic value. A transparent relation between value and composition is required to decide if the recycling process is cost effective for a particular waste stream. An objective and reliable quality control technique is needed in the recycling industry for the monitoring of both recycled flow streams and final products in the plant. In this work hyperspectral imaging technique in the near infrared (NIR) range (1000-1700 nm) was applied to identify unwanted plastic contaminants and rubber present in PVC coming from windows frame waste in order to assess a quality control procedure during its recycling process. To reach the previous mentioned goals a special designed HSI based platform was utilized to perform all the analysis. More in detail, the HSI based detection architecture was set up to allow not only to perform static, but also dynamic analysis, that is the possibility to carry out the tests on particles waste flow streams transported on a conveyor belt. Following this strategy the detection system faces the typical problems arising when an on-line sorting and/or quality control unit is utilised, with all the problems related to: i) the communications among the different hardware units, ii) the calibration and handling of the inspection devices, according to possible operative variations (i.e. PVC waste streams characteristics, flow stream speed), iii) an efficient data-flow control (i.e. continuous synchronisation and storage of the acquired signals) and the possibility to define, modify and add logics (i.e. off- and/or on-line sorting and/or certification procedures) for the characterization, inspection and quality control of materials according to their possible variations and/or new market constraints. Results showed as PVC, PE and Rubber can be identified adopting the NIR-HSI approach.

8774-61, Session PS

Optical diagnostics of ZrON/Si thin films formed by oxidation/nitridation of zirconium metal

Victor V. Atuchin, Vladimir Kruchinin, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation); Cheong Kuan Yew, Univ. of Malaya (Malaysia); Yew Hoong Wong, Univ. Sains Malaysia (Malaysia)

In this study, ZrO2 thin films were formed by simultaneous oxidation and nitridation of sputtered Zr on Si in N2O ambient. An ultrathin layer (~ 3 nm) has been formed by ZrO2 incorporated with nitrogen to generate a non-stoichiometric ZrO2 (ZrON) film. The nitridation effect in this process is postulated to provide good optical and electrical properties of ZrON films. Bare n-type RCA cleaned (100) Si wafers (1-10 ?cm) were used as the substrate in this study. Subsequently, the substrate was dipped into diluted HF solution (1 HF : 50 H2O) to remove native oxide of the wafer. By utilizing a RF sputtering system (Edwards Auto 500), few-nanometer thick Zr film was deposited on the Si substrates. The working pressure, RF power, inert Ar gas flow, and deposition rate were regulated at 1.2?10-7 Torr, 170 W, 20 cm3/min, and 0.2 nm/s, respectively. After the deposition, samples were loaded into a horizontal tube furnace and heated up from room temperature to 500-900oC at a fixed heating rate of 10oC/min in an Ar flow ambient. Once the set temperature was achieved, N2O gas was introduced with a flow rate of 150 mL/min for a set of durations before allowing the furnace to be cooled down to room temperature in an Ar ambient. Evaluations of structural and chemical properties of the samples were carried out by various characterization techniques such as XPS, XRD, RHEED. Dispersive optical parameters of ZrON/Si system were measured with spectroscopic ellipsometry (SE) using ELLIPS-1771 SA (Russia) spectroscopic ellipsometer. The spectral dependencies of ellipsometric angles ? and ? were measured in the wavelength range ? = 250-1100 nm with spectral resolution of 2 nm. The four-zone method of measuring with subsequent averaging over all four zones was used in the experiment. For ZrON/Si system the model of air – (homogeneous isotropic film) – (homogeneous isotropic film) – Si substrate was used in calculations. Formation of interface SiO2-type layer during oxidation/nitridation treatments at T > 700?C has been detected by SE measurements.

8774-62, Session PS

Polymer planar Bragg grating for sensing applications

Manuel Rosenberger, Univ. of Applied Sciences Aschaffenburg (Germany); N. Hartlaub, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Georg Koller, Stefan Belle, Univ. of Applied Sciences Aschaffenburg (Germany); Bernhard Schmauss, Friedrich-Alexander-Univ. Erlangen-Nürnberg (Germany); Ralf Hellmann, Univ. of Applied Sciences Aschaffenburg (Germany)

Bragg gratings have become indispensable as optical sensing elements and are already used for a variety of technical applications. Mainly, silica fiber Bragg gratings (FBGs) have been extensively studied over the last decades and are nowadays commercially available. Bragg grating sensors consisting of other materials like polymers, however,

have only recently come into the focus of current research. It is already apparent that polymers exhibit significantly different properties advantageous for many sensing applications and therefore provide a good alternative to silica based devices. In addition, polymer materials are inexpensive, simple to handle as well as available in various forms like liquid resists or bulk materials. Accordingly, polymer integrated optics attract increasing interest and can serve as a substitute for optical fibers.

We report on the fabrication of a planar Bragg grating sensor in bulk Polymethylmethacrylate (PMMA). The sensor consists of an optical waveguide and a Bragg grating, both written simultaneously into a PMMA chip by a single writing step (SWS), for which, a phase mask covered by an amplitude mask was placed on top of the PMMA chip and exposed to the UV radiation of a KrF excimer laser. Depending on the phase mask period, different Bragg gratings reflecting in the telecommunication wavelength range are fabricated and characterized. Reflection and transmission measurements show a narrow reflection band and a high reflectivity of the polymer planar Bragg grating (PPBG). After connecting to a single mode fiber the portable PPBG based sensor was evaluated for different measurands like temperature, humidity and strain. The sensor performance was compared to already existing sensing systems. Due to the obtained results as well as the rapid and cheap fabrication of the sensor chip our PPBG qualifies for a low cost sensing element.

8774-63, Session PS

Low noise omnidirectional optical receiver for the mobile FSO networks

Karel Witas, Stanislav Hejduk, Vladimir Vasinek, Jan Vitasek, Jan Latal, Technical Univ. of Ostrava (Czech Republic)

A high sensitive optical receiver design for the mobile free space optical (FSO) networks is presented. There is an array of photo-detectors and preamplifiers working into same load. It is the second stage sum amplifier getting all signals together. This topology creates a parallel amplifier with an excellent signal to noise ratio (SNR). An automatic gain control (AGC) feature is included also. As a result, the effective noise suppression at the receiver side increases optical signal coverage even with the transmitter power being constant. The design has been verified on the model car which was able to respond beyond the line of sight (LOS).

8774-64, Session PS

Monte Carlo simulation of spatial reflectance pattern of translucent material with subsurface structure

Harri J. Juttula, Anssi J. Mäkynen, Univ. of Oulu (Finland)

Translucent materials allow light to travel inside them while exposed to scattering or absorption events. Wood is an example of translucent material with long cylindrical cells forming an anisotropic internal structure. The most characteristic scattering phenomenon of laser light associated with wood surface is the elongation of spatial reflectance pattern in the direction of wood cells which is called the tracheid effect. We used Monte Carlo simulations of light to reproduce this effect with a model of translucent material with internal cylinder network structure and used the simulated backscattering patterns to predict macroscopic physical properties of the model. We created a simple model of subsurface structure with 30 ?m wide and semi-infinite long uniformly placed hollow cylinders surrounded by wall material with refractive index of 1.55 and known absorption and scattering coefficients. The cylinders represent the tracheid cells of softwood which can be several millimeters long and they were filled with either air or water to produce a macroscopic moisture content of the simulated material. Different densities of material were modeled by varying the diameters of the cylinders. The effects of different moisture contents, densities and surface profiles to angularly and spatially resolved reflectance of light were observed by analyzing the shape of the simulated backscattering patterns and PLS models were created to predict moisture and density of models with unknown properties. Moisture was found to increase transmission and distance that light travels inside the material and also turning the orientation of the highest contour level by 90 degrees with respect to that of a dry sample while the size of the scattering pattern was found out to decrease as density increased. Density and moisture errors of PLS model predictions were 0.018 g/mm3 and 10.97 % with R2 values of 0.921 and 0.925, respectively.

8774-65, Session PS

PCF interferometer based temperature sensor with high sensitivity

Fernando C. Fávero, Ron Spittel, Manfred Rothhardt, Jens Kobelke, Hartmutt Bartelt, Institut für Photonische Technologien e.V. (Germany)

In this work, the use of a photonic crystal fiber (PCF) with a highly Germanium doped core is exploited as temperature sensor for the first time (to our knowledge). The PCF has an outer diameter of 125 µm and consists of a microstructured cladding with an average pitch and hole diameter of ?=4.6 µm and d=1.0 µm, respectively. A short PCF stub (~2.0 mm) is used for the preparation of an interferometer. The PCF is spliced between single mode fibers (SMF), meaning that the PCF holes are fully collapsed in the splicing region while the Ge-doped core is still present. The splice parameters were changed to make a short collapse region of (200±30) microns. The first splice is used to excite both, the fundamental core mode and multiple higher order cladding modes by applying a core-to-core offset. The second splice acts as spatial filter to detect only the light which is guided in and near the core. The result is a sinusoidal spectral interference pattern in transmission, which can be explained theoretically by the use of numerical simulations using a finite element method.

The interferometer is heated up to 500°C and the total wavelength shift with the temperature variation found to be 74 pm/°C which is more than 5 times higher than a fiber Bragg grating at 1550 nm (13pm/°C).

The PCF interferometer preparation requires only a few steps, cleaving and splicing the fibers. The short length, the high thermal sensitivity and stability of the structure make the device attractive for many sensing applications including high temperature ranges.

8774-66, Session PS

Coupling conditions for quasi-single mode optical fibers with different refractive index profile

Petr Siska, Jan Latal, Petr Koudelka, Jan Vitasek, Technical Univ. of Ostrava (Czech Republic); Ivan Kasik, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Vladimir Vasinek, Technical Univ. of Ostrava (Czech Republic)

This article is dealing with problems connected with coupling conditions for different types of quasi-single mode optical fibers with various refractive indices of core and cladding. The description of coupling conditions repeatable measurement and measurement of optical beam by the slit method is also presented. The heads of quasi-single mode optical fibers were measured and observed with the help of CCD camera and microscope. These instruments allow measuring of optical power redistribution in modal field.

8774-67, Session PS

Design and in-flight performance of ZY-3 satellites cameras

Hongyan He, Weijun Gao, China Academy of Space Technology (China)

ZiYuan 3(ZY-3) satellite is the latest stereo imaging satellite of China. It was launched successfully launched on Jan,9th,2012. And it has achieved many high-quantity images. The mission of ZY-3 satellite is to provide sufficient data to generate 1 to 50,000 scale-based maps over China. There are four optical sensors(cameras) in the satellite, including three panchromatic cameras and a multispectral camera.

The fore,back and nadia camera provide resolution of 3.5m, 3.5m and 2.1m respectively. The multispectral camera provides resolution of 5.8m. The cameras adopt many advanced design to meet the mapping requirement with high performance.

This paper briefly introduces the cameras' design and performance, which mainly include the design result and their in-flight performance. By comparing and analyzing the testing results of two states(before launch and after launch), we get to know how the optical sensor' performance is changed. Meanwhile, the paper provides data processing methods, especially about the radiometric calibration after launch. During a nearly year, several calibrating work has been finished. The paper introduces the calibrating method and data processing method. At last, the processed result of cameras will be listed, which can be used to calibrate the satellite images.

8774-69, Session PS

Sensitivity of Wood-Rayleigh anomalies in metallic nanogratings

Armando Ricciardi, Univ. degli Studi del Sannio (Italy); Silvio Savoia, Univ. degli Studi del Sannio (Italy) and Waves Group (Italy); Alessio Crescitelli, Univ. degli Studi del Sannio (Italy); Emanuela Esposito, Istituto di Cibernetica Eduardo Caianiello (Italy); Vincenzo Galdi, Andrea Cusano, Univ. degli Studi del Sannio (Italy)

Spectral anomalies in the response of diffraction gratings constitute a subject of longstanding interest in optics. Basically, two types of anomalies can be identified: sharp anomalies, due to the passing-off of a spectral diffraction order, and diffuse anomalies arising from the excitation of surface waves (both photonic and plasmonic). The former, typically referred to as Rayleigh anomalies (RAs), occur when the m-th diffraction order becomes tangent to the plane of the grating causing abrupt intensity variations at wavelengths given by the well-known grating formula ?RA(m)= (na??)/m (valid for normal incidence), where ? is the period of a grating immersed in a medium with refractive index na. These wavelengths are intrinsically sensitive to changes of the surrounding ambient. In this work, with reference to a hybrid metallo-dielectric 1D grating, we provide numerical and experimental evidence that a significant difference exists between bulk and surface sensitivities in nanograting based on RAs when employed for sensing the surrounding refractive index. Indeed, we demonstrate that recently proposed sensing schemes based on RAs in optical nanogratings (exhibiting a sensitivity determined solely by the grating period) can only be applied in the presence of bulk analytes.

In particular here we analyze a hybrid metallo-dielectric structure consisting of a dielectric (ZEP) 370 nm thick layer backed by a silicon substrate and patterned with a 1D lattice with period ? =1500 nm and a duty cycle DC=0.25. A 30 nm thick film of gold is deposited on both the ridges and grooves of the dielectric grating. In order to experimentally estimate the surface sensitivity, we deposited on top of the structure nanosized dielectric layers of SiO2 of thickness 30 and 60 nm.

In the presence of thin overlays of analytes, we demonstrate that the (surface) sensitivity deteriorates up to two orders of magnitude by comparison with its bulk value.

This behavior, from the physical viewpoint, is consistent with the poorly localized character of the field distributions associated with RAs. This aspect is of fundamental importance as it severely limits the practical applicability of these devices to chemical and label-free biological sensing where refractive index changes induced by chemical or biological interactions are related and limited to a thin layer. Since the same structures can naturally support SPRs (with a strongly localized field distribution at the sensor surface), more effective design strategies may be followed in order to attain much higher surface sensitivities (>1000 nm/RIU).

8774-70, Session PS

Measurement of magnetic circular dichroism loss in a ring laser

Zhiguo Wang, Jie Yuan, Fei Wang, Guangzong Xiao, Xiaochun Liu, National Univ. of Defense Technology (China)

Ring laser gyros have been widely used in such areas as inertial technology, fundamental physics and geophysics due to their capability to measure rotation rates accurately with the frequency difference between counter traveling wave modes. The subtle backscattering on the imperfect mirror, however, can lead to severe lock-in problem. Laser gyros are often mechanically dithered to overcome the lock-in problem. Although the mechanically dithered gyros have reached very high precision, the moving parts can cause many disadvantages, such as acoustic noise, mechanical disturbance and coning error.

Four-mode differential laser gyros which use pure optical method to eliminate lock-in do not have the said disadvantages. But their precision can be affected by many factors. One of them is magnetic circular dichroism loss (MCDL) which is a kind of nonreciprocal effect leading to beat-note instability. The MCDL is so small that it is hard to be measured directly with current cavity loss measurement technique. However, theoretical analysis indicates that when discharge current varies, the ratio of beat-note change and reciprocal bias change equals to the ratio of MCDL and cavity loss. As a result, the MCDL can be measured indirectly. Experimental results showed that the ratio is 0.0001 for a four-mode differential laser gyro. We measured the cavity loss with time lens method. According to these results, the MCDL is obtained, which is close to the numerical simulation result.

8774-71, Session PS

Numerical analysis of diffraction loss characteristics in nonplanar ring resonator

Zhiguo Wang, National Univ. of Defense Technology (China); Jie Jie Yuan, NUDT (China); Xiaohu Liu, Fei Wang, Guangzong Xiao, National Univ. of Defense Technology (China)

Ring lasers can be used to sense rotation rates with its beat frequency between the clockwise and counterclockwise modes. The output signal at zero rotation rate is called null shift, which is a result of nonreciprocal effects except rotation. One potential nonreciprocal effect comes from improperly designed aperture, which is used to suppress off-axis modes in the ring laser. Therefore, we will make some optimization so as to minimize nonreciprocal loss caused by different diffraction loss of the modes.

The ring cavity comprises four mirrors and an aperture. The influence of mirrors' limited size is neglected because their sizes are much larger than that of the aperture. And then we established the generalized diffraction integral equation to analyze the optical field in nonplanar ring resonators. The equation is solved numerically by using finite element transfer matrix method and consequently the diffraction loss and optical field distribution are obtained.

We discussed the characteristic of diffraction loss in a nonplanar ring resonator with Faraday cell? including the variation of diffraction loss and nonreciprocal loss as a function of aperture size, aperture position and magnetic lens effect of Faraday cell. It is shown that asymmetric aperture position in company with ray decentration will cause nonreciprocal differential direction diffraction loss; magnetic lens effect will lead to severe nonreciprocal magnetic circular dichroism loss. A larger aperture size will reduce these nonreciprocal diffraction losses, so it is useful to adopt large aperture as long as the off-axis mode is suppressed. These foundings are significant to the improvement of nonplanar ring cavity for ring laser gyros.

Conference 8775: Micro-structured and Specialty Optical Fibres II

Monday - Tuesday 15–16 April 2013

Part of Proceedings of SPIE Vol. 8775 Micro-structured and Specialty Optical Fibres II

8775-1, Session 1

DNA biosensors implemented on PNA-functionalized microstructured optical fibers Bragg gratings *(Invited Paper)*

Alessandro Candiani, Sara Giannetti, Annamaria Cucinotta, Alessandro Bertucci, Roberto Corradini, Univ. degli Studi di Parma (Italy); Maria Konstantaki, Foundation for Research and Technology-Hellas (Greece); Walter Margulis, Acreo AB (Sweden); Stavros Pissadakis, Foundation for Research and Technology-Hellas (Greece); Stefano Selleri, Univ. degli Studi di Parma (Italy)

Microstructured Optical Fibers (MOFs) and Photonic Crystal Fibers (PCFs) are versatile photonic platforms for developing opto-fluidic sensing elements of new functionalities. The capillaries running along the fiber length constitute a powerful microfluidic platform that can be surface functionalized for performing selective sensing experiments. Long Period Gratings (LPGs) or Bragg Gratings (BGs) inscribed in MOFs represent a further powerful tool that can be efficiently used for interrogating the changes occurring in the functionalized capillaries.

In the present work we considered two different microstructured optical fibers: the first one was a grape-fruit geometry MOF having 5 holes of 20.8?m diameter, forming an outer core of 16.1?m, which includes a 3.5%wt Ge doped socket of diameter 8.5?m. The second fiber was a Large Mode Area (LMA-10) MOF, having the hexagonal holes arrangement typical of such fibers. The inner surface of both MOFs, where a strong Bragg grating was previously inscribed using a standard phase mask and 193nm excimer laser set-up, has been functionalized using Peptide Nucleic Acid (PNA) probe, an OligoNucleotide (ON) mimic that is well suited for specific DNA target sequences detection. The DNA molecules solution, matched with the PNA probes, has been infiltrated inside the fiber capillaries and hybridization has been realized. Oligonucleotide-functionalized gold nanoparticles (ON-AuNPs) were infiltrated and used to form a sandwich-like system to increase the refractive index contrast and to achieve signal amplification. Spectral measurements made in both fibers in reflection mode showed a clear wavelength shift of the resonant peak. Several experiments have been carried out using identical DNA concentrations and the same modulations have been observed, proving the reproducibility of the results. Measurements have also been made using mismatched DNA solution, containing a single nucleotide polymorphism, demonstrating the high selectivity of the sensors. A comparison between the results of the two MOFs will be presented, demonstrating the feasibility of using such an approach in biosensing.

8775-2, Session 1

Exposed-core chalcogenide microstructured optical fibers for chemical sensing

Johann Trolès, Perrine Toupin, Univ de Rennes 1 (France); Laurent Brilland, PERFOS (France); Catherine Boussard-Plédel, Bruno Bureau, Univ. de Rennes 1 (France); Shuo Cui, University of Rennes (France); David Méchin, PERFOS (France); Jean-Luc Adam, Univ. de Rennes 1 (France)

Chemical bonds of most of the molecules vibrate at a frequency corresponding to the near or mid infrared field. It is thus of a great interest to develop sensitive and portable devices for the detection of specific chemicals and biomolecules for various applications in health, the environment, national security and so on. Optical fibers define practical sensing tools. Chalcogenide glasses are known for their transparency in the infrared optical range and their ability to be drawn as fibers. Such optical fibers can transmit light from 2 to 20 µm depending on the composition of the glass constituting the fiber. They are consequently good candidates to be used in biological/chemical sensing. For that matter, in the past decade, chalcogenide glass fibers have been successfully implemented in evanescent wave spectroscopy experiments, for the detection of bio-chemical species in various fields of applications including microbiology and medicine, water pollution and CO2 detection.

Different types of fiber can be used: single index fibers or microstructured fibers. Besides, in recent years a new configuration of microstructured fibers has been developed: microstructured exposed-core fibers. This design consists of an optical fiber with a suspended micron-scale core that is partially exposed to the external environment. This configuration has been chosen to elaborate, using the molding method, a chalcogenide fiber for chemical species detection. The sensitivity of this fiber to detect molecules such as propan-2-ol and acetone has been compared with those of single index fibers. Although evanescent wave absorption is inversely proportional to the fiber diameter, the result shows that an exposed-core fiber is much more sensitive than a single index fiber having a twice smaller external diameter.

8775-3, Session 1

Competitive Raman gain and signal attenuation in PCF: an integrated theoretical and experimental study using SERS nanotags

Polina Pinkhasova, Svetlana A. Sukhishvili, Henry H. Du, Stevens Institute of Technology (United States); Jiri Kanka, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

The competitive Raman gain and scattering/absorption-induced signal attenuation over the length of a waveguide decorated with SERS-active Ag or Au nanoparticles depends critically on the particle size and coverage density. We have carried out a combined theoretical and experimental investigation of this complex interplay to ascertain optimal nanoparticle parameters for SERS-active photonic crystal fiber sensors. In particular, discrete dipole approximation (DDA) and finite difference time domain (FDTD) simulation methods have been used to evaluate the interaction of the evanescent field of the guided core with immobilized nanoparticles (diameter: 20-100 nm, coverage: 0.1-5 particles/µm2). Favorable nanoparticle parameters have been experimentally assessed using well-behaved, individually SERS-active Au shell-Ag core nanotags that are immobilized on the cladding air channels of a suspended core PCF. The theoretical calculations and experimental findings will be compared and contrasted, using the optical path length (i.e., fiber length) as a means of further increasing the detection sensitivity of the SERS-active PCF.

8775-4, Session 1

Polarization maintaining evanescent field sensor for measuring liquid refractive index change

Rim Cherif, Amine Ben Salem, Mourad Zghal, SUP'COM (Tunisia)

Extensive researches in the development of evanescent-field-based optical fiber sensors have been recently devoted to design refractometric or absorption sensors for real-time diagnosis. These sensors exploit the fractional power propagating in the evanescent field in order to analyze and determine the refractive index (RI) change of the specimen surrounding the optical waveguide. By using elliptical photonic nanowires, larger fractional power propagating in the evanescent field and polarization maintaining are obtained [1]. By inserting these elliptical photonic nanowires in Mach-Zehnder interferometer (MZI), the MZI-based sensor is found to offer great potential with its high phase sensitivity to the refractive index variation and allow the development of highly-sensitive robust sensors.

In this work, we propose a new design of MZI structure assembled with two arms composed of elliptical silica photonic nanowires with 800 nm diameter and immersed in aqueous solution. The first arm is used as reference and kept isolated from the specimen. The second one is considered as sensing arm exposed to the specimen with a certain sensitive-area-length. By applying a full vectorial finite element method, single-mode operation, polarization maintaining and very high sensitivity are achieved by simply using elliptical nanowires. Using the highly-sensitive versatile interferometry technique, the phase shift from both arms is determined and consequently the specimen's information can be retrieved. The proposed design is found to enhance considerably the sensitivity and determine the very small RI change of liquids. This is the first time to our knowledge that the sensitivity of the sensor can be controlled by the ellipticity modification of photonic nanowires. Therefore, we show that 800 nm-elliptical nanowires are very promising waveguides for refractometric sensing without the need to extremely reduce the nanowires size up to 400 nm to get comparable performances as it happens with the circular ones.

We tested the sensor by considering the specimen to be analyzed with different concentrations for probing lights at short optical wavelengths (650 nm and 970 nm) in order to avoid the high water absorption. In fact, the sensitivity of detecting benzene solutions in water is evaluated to be 4.17 rad/μm. Then, the detection of solutions with different NaCl concentrations is achieved with high sensitivity of 4.67 rad/μm demonstrating that the sensor is capable of detecting a RI variation of 10-6 with only 1-mm sensitive-area-length. Thus, the proposed MZI-based elliptical-sensor shows to be very attractive for compact, flexible and high sensitive biochemical sensing.

[1] A. Ben Salem, R. Cherif, and M. Zghal, "Rigorous optical modeling of elliptical photonic nanowires," J. Lightw. Technol. 30, 2176-2180 (2012).

8775-5, Session 1

Photonic crystal fiber coil sensor for water-depth sensing

Chin-Ping Yu, Chen-Feng Fan, National Sun Yat-Sen Univ. (Taiwan)

Photonic crystal fibers (PCFs) with an air-hole array in the cladding region have been widely adopted in many optical applications, including waveguides, switches, interferometers and filters. Recently, sensors based on PCFs have attracted a lot of attention due to their extra-low sensitivity to temperature. They can be utilized in sensing of bending, refractive index, displacement, and pressure with negligible temperature disturbance. In this paper, we fabricate a PCF coil sensor for water-depth sensing by simply winding a PCF on a plastic tube. The PCF we used is LMA-10 PCF from NKT Photonics A/s. The diameter of the tube and the fiber turns are 1.2 cm and 24, respectively. The PCF coil is then placed into a Sagnac fiber loop. Due to the bending induced along the PCF, slight birefringence is introduced in the PCF and we can observe interference pattern in the output spectrum of the PCF coil. The fabricated PCF coil is first horizontally immersed into water. As we increase the depth of the PCF coil in the water, the interference pattern moves toward shorter wavelength. A nonlinear relationship between the depth and the wavelength shift can be obtained. We have also measured the interference spectrum by vertically immersing the PCF coil into water. The interference spectrum shows a blue shift, and we can observe a linear relationship between the depth of the PCF coil in water and the wavelength shift. The measured water-depth sensitivity for vertically immersion is -11.658 nm/cm, which shows that the fabricated PCF coil is quite useful in sensing of water depth.

8775-6, Session 2

Mid-infrared supercontinuum generation in chalcogenide and tellurite suspended core fibers

Frederic Desevedavy, Inna Savelii, Ousama Mouawad, Jean-Charles Jules, Grégory Gadret, Bertrand Kibler, Julien Fatome, Pierre-Yves Bony, Jérémy Picot-Clemente, Clement Strutynski, Univ. de Bourgogne (France); Hiroyasu Kawashima, Weiqing Gao, Tomas Kohoutek, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan); Frédéric Smektala, Univ. de Bourgogne (France)

In the last years non silica glass optical fibers have been the subject of many studies for their original properties in the mid infrared. Indeed heavy oxides or chalcogenide glasses show large transparency in the mid infrared, high refractive indices and high non linear refractive indices compare to silica ones.

We present our recent results concerning the elaboration and characterization of chalcogenide and tellurite suspended core fibers based on the sulfide glass As2S3 and tellure-zinc-sodium one (TZN).

Crucial efforts has been made to reduce material losses especially around 3 μm which correspond to hydroxyl (OH) absorption and hydrogenate species.

To decrease losses on tellurite glasses at this wavelength we developed newcompositions based on fluoride reactants associated with new process of synthesis. More precisely we used reactive atmosphere processing to decrease the content of impurities and improve the glass transmission.

To prepare our preforms, we used a drilling technique which is an original process on such soft glasses. Fibers are drawn with our drawing tower under gas pressure. The fibers attenuation are measured by the cut back technique using a FTIR spectrometer and compare for some wavelenght with measurements done by means of monochromatic lasers (1.06 and 1.55μm).

Dispersion has been modelised for different fibers depending of the material and the geometry, mainly the core diameter, and compared with the measurement of the dispersion between 1.2 and 1.7 μm. Based on these results we fabricated suspended core fibers in order to be in anomalous dispersion regime at the pump wavelength. The obtained tellurite suspended core fiber exhibits a core diameter of approximately 3 μm, corresponding to a zero dispersion wavelength at 1.6 μm. The core diameter of the sulfide is around 3.2 μm corresponding to a zero dispersion wavelength of 2.3 μm.

A Ti:Sapphire synchronously pumped optical parametric oscillator delivering 200 fs time duration pulses at a repetition rate of 76 MHz operating between 1.7 and 2.5 μm is used for measurements of the non linear properties.

The obtained microstructured fibres have been pumped in their anomalous dispersion regime. We obtain supercontiuums of almost two octave large, depending of the power, extending up to 3 μm for the TZN fiber with an input pump power of 112 mw and up to 3.5 μm for the As2S3 glass with an injected pump power of 70 mW. We worked with short lenght, 6 cm for the tellurite fiber and 4.5 cm for the chalcogenide one. In both cases, supercontinuum generation is mainly driven by self-phase modulation, soliton fission and Raman based soliton self-frequency shift, which allow extending the resulting spectrum towards the mid-infrared. The lower edge of the supercontinuums is mainly enlarged through phase-matched dispersive wave generation. The agreement between simulated spectrums and measured ones is good and highlight the losses impact especially the ones of hydrogenate impurities. This which will be discussed as well as the compromise we have to make between core size related to the nonlinear coeffcient we want as high as possible and the coupling coeffcient between the pump source and the tested fibre.

8775-7, Session 2

Preparation and characterization of Bragg fibers with air cores for transfer of laser radiation

Vlastimil Matejec, Ivan Kasik, Ondrej Podrazky, Jan Aubrecht, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Michal Frank, Michal Jelínek M.D., Václav Kubecek, Czech Technical Univ. in Prague (Czech Republic)

Recently, silica optical fibers have been investigated for using in telecommunication lines, sensors and also for delivery of high powers. The delivery of high powers has been employed in medicine, solar systems for heating, lighting and electricity production or in industry for metal welding or hardening. Different types of optical fibers have been tested for such purposes icluding silica fibers, plastic fibers,

sapphire fibers, chalcogenide fibers, hollow-core fibers, Bragg fibers or photonic crystal fibers. Recently, photonic crystal fibers have also been developed and tested for laser power delivery at 1064 [1] or 2960 nm [2]. Bragg fibers with silica cores, large fundamental-mode areas and low optical losses suitable for energy delivery have been designed and prepared [3]. Such fibers can be fabricated by the MCVD method which is less complicated technique than methods used for preparation of photonic crystal fibers. This paper presents results of theoretical design, preparation and characterization of Bragg fibers with air cores designed for delivery of laser radiation at 1064 nm. Results of the characterization of these fibers are compared with those obtained on Bragg fibers with silica cores.

The Bragg fibers investigated in the paper consist of the core with a refractive index equal to that of air or silica which is surrounded by three pairs of circular layers. Each pair is composed of one layer with a high and one layer with a low refractive index with a refractive-index contrast up to 0.035. Spectral dependence of the complex propagation constant of the fundamental optical mode in such a structure has been evaluated on the basis of waveguide optics [4].

Preforms of the designed Bragg fibers were prepared by the MCVD method using germanium dioxide, phosphorous pentoxide and fluorine as silica dopants. The fibers with silica and air cores have been drawn from the preforms by controlling the drawing temperature and velocity. In the paper results of characterization of the fibers with optical microscopy and by measuring their refractive-index profiles, losses and angular distributions of the output optical power will be presented. Bending losses and results of tests of the fibers for delivery power of a pulse Nd:YAG laser at 1064 nm are also discussed in the paper.

This research is supported by the Czech Science Foundation (contract 102/12/2361)

[1] J.D. Sheppard et al., Opt. Express 12 , 717-723, 2004.

[21] A. Urich et al., Opt. Express 20, 6677-6684, 2012.

[3] M.E. Likchachev et al., Quant. Electron.36, 582-586, 2006.

[4] P. Yeh, A. Yariv, J. Opt. Soc. Am. 68 , 1196-1201, 1978.

8775-8, Session 2

The influence of nanostructured optical fiber core matrix on the optical properties of EDFA

Jakub Cajzl, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic) and Institute of Chemical Technology (Czech Republic); Ondrej Podrazky, Jan Mrázek, Jan Aubrecht, Vlastimil Matejec, Pavel Peterka, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Pavla Nekvindová, Institute of Chemical Technology (Czech Republic); Ivan Kasík, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Erbium-doped fiber amplifiers (EDFA) are the most widely used optical amplifiers in photonics and optoelectronics. Er(3+) ions are used because of their three-level radiative transition I(11/2) ? I(15/2) with emission around the wavelength of 1.5 µm. Emission at 1.5 µm falls into the 3rd telecommunication window where the silica optical fibers exhibit the lowest optical attenuation. Nowadays, the attention is given to the development and characterization of nanostructured optically active materials. Special optical fibers with the nanostructured rare-earth (RE) doped matrix are known for their interesting optical properties. However, there is still known little about the influence of vicinity of RE ions in nano-scale on their luminescence properties. In this contribution we demonstrate the effect of the nano-structured matrix doped with erbium ions on the optical properties of prepared active fibers.

Several optical fibers with nano-structured core were drawn from preforms prepared by different techniques, i.e. by common doping from solution of erbium and aluminium ions, by deposition of the dispersed alumina nanoparticles with either Er(3+) ions or Er2O3, and by deposition of sol with the composition of erbium-doped YAG. Reference bulk samples were prepared by the solid-state approach and thermally treated by similar way as optical fibers. Prepared optical fibers and bulk samples were investigated by absorption spectroscopy and steady-state and time-resolved luminescence spectroscopy.

Reference samples were analyzed by common structural techniques such as X-ray diffraction and Raman spectroscopy for the determination of the crystalline properties of formed nano-structures. Optical properties of optical fibers were related to those of reference bulk samples.

It was found that the presence of nanocrystals inside the fiber core improves the fiber-core homogeneity and decreases the optical background losses. The presence of nano-structured alumina inside the core matrix enhances the luminescence properties of Er(3+) ions. The effect of nanostructure to the further optical properties is discussed in the contribution.

Acknowledgement:

This research was financially supported by the Czech Science Foundation under project N° 102/10/2139.

8775-9, Session 2

Large core Yb-doped optical fiber through vapor phase doping technique

Maitreyee Saha, Atasi Pal, Mrinmay Pal, Ranjan Sen, Central Glass and Ceramic Research Institute (India)

Rare earth (RE) doped optical fibers have become an area of active interest for producing high power fiber lasers for industrial, medical and strategic applications. A number of methods have been followed to incorporate RE ions into the silica glass structure, among which solution doping technique is most popular due to its simplicity and flexibility. However, it suffers from poor repeatability and reached the limit regarding large core size which is essential for laser fibers. For these reasons, vapor phase chelate delivery technique based on high temperature sublimation of RE chelate compounds is gaining much importance in recent times. But till date, very few fibers have been made by this process due to many critical challenges of this technique such as condensation and/or decomposition of precursor materials prior to the reaction zone, variation in dopant concentrations over the length of the preform etc. This paper presents standardized fabrication process of large core Yb-doped fibers through vapor phase doping technique by optimizing the process parameters which can be reliably adopted for fabricating different designs of RE doped preforms/fibers suitable for their application as fiber lasers.

The preform fabrication was carried out using a specially constructed MCVD system containing High Temperature Vapor Delivery Unit with sublimators, highly heated delivery lines, unique rotary seal and ribbon burners. The solid Yb-chelate compound [Yb(thd)3] and anhydrous AlCl3 were heated in the respective sublimators at high temperature and the generated vapors were transported to the reaction zone by using Helium as carrier gas. The advantage of the method lies in deposition of Al2O3 and Yb2O3 in vapor phase simultaneously in combination with silica and other refractive index modifying dopants during formation of sintered core layer. Multiple core layers were deposited in a reproducible manner through well controlled precursor vapor generation for fabricating large core fibers with desired numerical aperture. This was followed by collapsing of substrate tube at high temperature in stepwise manner. The process parameters have been precisely optimized to transport Al-salt and RE-chelate compounds to the reaction zone without decomposition and/or condensation of precursor materials in the upstream delivery lines. Thus variations of dopants concentrations along the length of the preform have been minimized to <1% and good repeatability of the process has also been achieved.

The significant outcome of the present work is development of large core Yb-doped optical fibers with core diameter upto 40 µm with respect to an overall diameter of 125 µm, numerical aperture in the range of 0.08-0.11 and maximum Yb3+ concentration as high as 1.6 mol%. Uniform Al3+ doping of about 27 mol% has been achieved devoid of any “star-like” imperfection at the core-clad boundary, which is the highest Al-doping in the silica fiber to the best of our knowledge. The fibers also exhibited improved optical properties, reduced photodarkening effect and better lasing performance due to optimized composition, minimal central dip, smooth core-clad boundary and superior dopant uniformity. Laser output power of 20W at 1.06 µm with efficiency of 76% has been successfully demonstrated from the fabricated fibers.

8775-10, Session 3

Silica-based UV-fibers for DUV applications: current status *(Invited Paper)*

Karl-Friedrich Klein, Cornell P Gonschior, Technische Hochschule Mittelhessen (Germany); Hanns S Eckhardt, Tec 5 (Germany); Moritz B Klein, TransMIT GmbH (Germany); Valery Khalilov, John Shannon, MOLEX - Polymicro (United States)

Over more than two decades, all-silica multimode fibers for UV applications has been improved. Especially two parameters of the the light-guiding core material are relevant: the DUV basic attenuation below 200 nm and the UV resistance expressed by UV induced losses.

The last parameter, the spectral stability, has been mainly characterized using deuterium lamp with a broadband spectrum: UV-absorption bands at 215 nm, around 250 nm and at 265 nm are generated during UV-light transportation. In addition, these induced losses generated by pulsed UV and NUV/violet lasers due to two photon-absorption or due to two-step processes were studied, too.

We will describe the current status of basic attenuation and UV resistance, including permanent and transient defects using a test set-ups now available for production. Especially, the core diameter and the spectral power spectrum of the light-sources had been taken into account. After the introduction of the test ste-up and experimental results, some recommendations for a test standard will be given. Here, the length-dependence of spectral UV-damage due to the variation of the power spectrum along the fiber is described.

Furthermore, few-mode fibers are of interest in the NUV region for laser delivery systems, especially at 266 and 355 nm wavelengths using the harmonics of pulsed Nd-YAG lasers. The current status of spectral laser-induced UV-damage at 355 nm will be compared with above results using deuterium lamp; in addition, the temperature- dependent recovery of the permanent defects will be shown and discussed, too. .

8775-11, Session 3

Generation of optical frequency combs in fibres

Marina Zajnulina, Jose Manuel Chavez Boggio, Leibniz-Institut für Astrophysik Potsdam (Germany); Andres A. Rieznik, Instituto Tecnológico de Buenos Aires (Argentina) and Consejo Nacional de Investigaciones Científicas y Técnicas (Argentina); Roger Haynes, Martin M. Roth, Leibniz-Institut für Astrophysik Potsdam (Germany)

Optical frequency combs (OFCs) generated in passively mode-locked lasers have revolutionized such scientific areas as metrology and spectroscopy. They are also promising for the needs of astronomical research where they can be used for high-precision wavelength calibration of optical or NIR spectrographs. Although the OFCs can be meanwhile generated in compact systems, the line spacing reaches up to a few GHz, whereas for astronomical applications the required spacing is up to some THz. In this work, we propose a system for generation of OFCs which is comparably simpler build, compact, stable, and low-cost. The initial field consisting of a sinusoidal wave, which was generated using a fix and a tunable CW laser, propagates through three nonlinear stages (fibres). In the first fibre, the sinusoidal wave gets reshaped and compressed into a train of soliton-like pulses. In the second one, these quasi-solitons are simultaneously amplified and strongly compressed to sub-100fs-pulses. Finally, by propagating through a low-dispersion fibre, they get spectrally broadened. The requirements we put on the system are the following: it should produce stable ultra-short pulses with minimum noise and, in the end, a frequency comb with a bandwidth as broad as possible. For that purpose, we have numerically investigated the evolution of the light pulses as a function of the input power, the dispersion and the nonlinear coefficients of the first fibre. Further, the optimum lengths of fibres 1 and 2 were optimized depending on the parameters mentioned above. The characteristics of the pulse compression in the first two stages are analysed by calculating the pulse-to-pulse coherence (temporal correlation), and evaluating the intensity noise of the pulse train. We show that low-noise few-kW peak-power pulses can be generated at 80 GHz repetition rate and with 30 W average power when the parameters are properly optimised. The numerical modelling is performed using the Generalised Nonlinear Schrodinger Equation which includes the Kerr and Raman nonlinearities, the influence of the higher-order dispersion, and an additional term describing the self-steepening of light pulses.

8775-12, Session 3

Effect of pump wavelength on self-induced laser line sweeping in Yb-doped fiber laser

Petr Navratil, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Pavel Peterka, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Václav Kubecek, Czech Technical Univ. in Prague (Czech Republic)

We have characterized Yb-doped fiber laser and determined the effect of pumping wavelength on self-induced laser line sweeping (SLLS). SLLS is a transient laser regime manifested by a relatively slow laser line shifting and usually observed in the near of pump laser threshold. The fiber laser under consideration is cladding-pumped by a temperature stabilised multimode laser diode (LD) at about 976 nm. The output wavelength of the diode is tunable by changing the diode temperature and current through the diode. The cavity of the laser is formed by cleaving the fiber laser ends.

Using this laser layout we made detailed study of sweeping dependencies on pump wavelength by adjustment of the LD current and temperature. The laser manifested laser line sweeping within the range of 5 - 8 nm on a wide scale of pump laser diode power and temperature; 15 - 45°C LD temperature scale and a pumping range reaching to more than twice the amount of excess over threshold. We performed the measurement of the laser line sweeping range, period and rate as the dependence of pump wavelength.

ACKNOWLEDGEMENT

This work was supported by the Ministry of Education, Youth and Sports of the Czech Republic, Contract No. ME10119 “FILA”, Academy of Sciences of the Czech Republic, project No. M100671202, the Institutional research plans MSM6840770022, and AV0Z20670512.

REFERENCES

[1] P. PETERKA, P. NAVRÁTIL, J. MARIA, B. DUSSARDIER, R. SLAVÍK, P. HONZÁTKO, and V. Kubecek. Self-induced laser line sweeping in double-clad Yb-doped fiber-ring lasers. Laser Phys. Lett. 9, 445 (2012).

[2] P. PETERKA, P. NAVRÁTIL, B. DUSSARDIER, R. SLAVÍK, P. HONZÁTKO, and V. Kubecek. Self-induced laser line sweeping and self-pulsing in double-clad fiber lasers in Fabry-Perot and unidirectional ring cavities. In SPIE 8433, 09-1 (2012).

[3] Ivan A. LOBACH, Sergey I. KABLUKOV, Eugeniy V. PODIVILOV, and Sergey A. BABIN. All-fiber broad-range self sweeping Yb-doped fiber laser. In SPIE 8237, 1C-1 (2012).

[4] A. V. KIRYANOV and N. N. ILICHEV. Self-induced laser line sweeping in an ytterbium fiber laser with non-resonant Fabry-Perot cavity. Laser Phys. Lett., 8(4):305 (2011).

8775-13, Session 3

Characterisation of optical pulses travelling through a photonic crystal fibre using Fourier-transform spectral interferometry

Tímea Grósz, Miklós Kiss, Attila P. Kovács, Univ. of Szeged (Hungary)

Photonic crystal fibres have recently received considerable attention since their properties, such as controllable dispersion and single-modal guidance can be adjusted by the proper design of their geometrical structure. Due to the uncertainties in modelling and manufacturing, it is necessary to measure the dispersion and to characterise the spatial and temporal profile of the pulse travelling through the fibre. Spectral interferometry is a widely used technique for the dispersion measurement of optical fibres.

Return to Contents

To retrieve the spectral phase of the fibres numerous evaluation techniques, such as the stationary phase point, the minima-maxima, the cosine function fit and the Fourier-transform method are used. It would be of great advantage to find the most precise one.

In this work we present a comparative study considering the evaluation methods mentioned above. Our experimental setup consisted of a Mach-Zehnder interferometer and a high resolution spectrometer (Ocean Optics, HR4000). The interferometer was illuminated by a Ti:sapphire oscillator (20 fs@800 nm). A 37 cm long photonic crystal fibre with reduced second and significant third and fourth order chromatic dispersion was inserted in the sample arm of the interferometer.

We found that the Fourier-transform method provided the dispersion coefficients, thus the spectral phase with the highest accuracy (the accuracy for the GDD, TOD, FOD and QOD is 2%, 2 %, 4 %, and 6 %, respectively). This technique proved to be very sensitive to the presence of the fourth and fifth order dispersion. Another benefit of the method is that it could detect phase jumps in the vicinity of the absorption valleys seen in the transmission spectrum of the fibre in contrast to the other procedures.

Having the spectral phase and the transmission of the fibre determined the temporal profile of the pulse was calculated by applying a Fourier-transform. As the Fourier-transform does not provide information about the relative position of the spectral components of the laser pulse in the time domain, a windowed Fourier-transform was used. We demonstrated that only spectral components with discrete frequencies were present in the laser pulse belonging to the higher transversal mode, and their positions in the time domain were measured.

If the spectral phase and the pulse shape are determined with the Fourier-transform method, three Fourier-transforms are being carried out in the process. When it is important to know the temporal profile of the pulse not only at a given point in space, but in a given plane, this characterisation process is time-consuming. Accordingly, we developed a novel simplified method based on Fourier-transform for the fast retrieval of the pulse shape in 2D which is presented in this paper. The evaluation is based on a modified spectral interferogram, thus it is enough to apply the Fourier-transform only once. Using this simplified method the time delay between the higher and the fundamental transversal modes in space was determined very quickly.

8775-14, Session 4

Numerical analysis of rocking filters fabricated in microstructured birefringent fibers

Jacek M. Olszewski, Alicja Anuszkiewicz, Waclaw Urbanczyk, Wroclaw Univ. of Technology (Poland)

Rocking filters are in-line optical fiber passive components playing the role of polarization spectral filters. Typically the rocking filter consists of a sequence of birefringent fiber segments twisted with respect to each other, which results in periodic coupling between polarization modes. When fractal waves coupled at successive twists from excited to not excited polarization modes are in phase, it results in significant energy transfer between the modes at specific wavelength. Typically the coupling between adjacent twisted segments is represented by rotation matrix in Jones or Stokes formalism. This is however a far simplification, as in the real rocking filter the adjacent fiber segments are separated by a transition region created by CO_2 laser or electrical arc with gradually changing twist rate. In this communicate we present a detailed analysis of the effect of twist profile in the transition regions on the coupling strength between the polarization modes and consequently on the rocking filter transmission characteristics. We demonstrate that continuous twist in the transition region results in dispersive character of the coupling coefficients. In consequence, the resonance depth in the transmission characteristics of the rocking filter is also dispersive. We present optimum design of the rocking filter fabricated in the microstructured fibers with highly dispersive birefringence profile. We also compare the transmission characteristics of the rocking filters fabricated in dispersive microstructured fibers and non-dispersive conventional fibers.

8775-15, Session 4

Coherent super-position of multiple beams in a large mode area fiber

Joseph W. Haus, Long Wang, Peter E. Powers, Andrew M. Sarangan, Univ. of Dayton (United States)

Among potential wide ranging applications the design of phase-locked fiber lasers based on the Talbot effect and a revival of the image is of primary interest in our talk. Fiber lasers have been identified as promising candidates for developing high power lasers with a high degree of coherence [1]. One reason is the simple geometry of optical fibers, which make alignment relatively easy and the laser cavity is compact. Also, optical fibers have inherently high surface area to active volume ratios which enables efficient cooling of the fiber system. Phase-locked fiber laser designs have been theoretically and experimentally demonstrated to be candidates for the future development of high power fiber lasers [2,3].

Previously, we introduced a Talbot mirror fiber device (TMFD) that could ultimately be useful for high power infrared fiber lasers. For demonstration purposes we perform initial experiments to test the TMFD concept in the visible to near infrared wavelength regime [4,5]. Our experiments were performed using a tunable Ti:Sapphire laser whose wavelengths spanned the wavelength range from 740 nm to 840 nm. We apply the beam propagation method (BPM) so that the dynamic field distribution can be easily and accurately determined as the beam propagates through the LMA fiber. In designing the experiment we determined the position where the image closely mimics the input pattern and compared our results between simulations and experiments.

In an all fiber application the input beam is shaped through a set of periodically placed single mode (SM) fibers. However, in our experiments we use a mask with holes fabricated on a fiber end to shape the input beam. The holes in the mask are arranged in hexagonal rings with the same nearest-neighbor separation. After coupling the multiple inputs into a LMA fiber, the beams interfere with one other during propagation. There are a set of partial image revivals which culminate in a revival overlap of the beams to reconstruct the input image.

References

[1] A. Galvanauskas, “High Power Fiber Lasers,” Optics and Photonics News 15, 42 (2004).

[2] Y. Zhou, L. Liu, C. Etson, Y. Abranyos, A. Padilla, and Y. C. Chen, “Phase locking of a two-dimensional laser array by controlling the far-field pattern,” Applied Physics Letters 84, 3025 (2004).

[3] B. He et al., “Experimental demonstration of phase locking of a two-dimensional fiber laser array using a self-imaging resonator,” Applied Physics Letters 92, 251115 (2008).

[4] R. Zhou, Q. Zhan, P. E. Powers, B. Ibarra-Escamilla, and J. W. Haus, “A multi-fiber laser using a phase-locking Talbot self-imaging effect,” Proc. SPIE 7839, 78390M-78390M-4 (2010).

[5] R. Zhou, Q. Zhan, P. E. Powers, B. Ibarra-Escamilla, and J. W. Haus, “An all fiber based Talbot self-imaging mirror device for phase-locking of a multi-fiber laser,” J. European Opt. Soc. 7, 12012 (2012).

8775-16, Session 4

Optimizing microfabricated liquid planar waveguides for microfluidic lab-on-chip flow cytometry systems

James Hoyland, Casper Kunstmann-Olsen, Horst-Günter Rubahn, Univ. of Southern Denmark (Denmark)

A versatile method for integrating liquid waveguides into PDMS microfluidic flow-cytometer chips is presented. By using a one-step direct replication, PDMS chips are produced with both fluidic and waveguide channels. Filling the waveguide channels with low-cost high refractive index media including gelatin and DMSO, a simple waveguide is created using the PDMS of the chip itself as cladding. Montecarlo ray-tracing is used to optimize waveguide geometry to maximize fluorescence signals from the weak, brief events seen in flow-cytometry. Straight waveguide structures with lengths up to

20mm and and curved structures with bend radii down to 5mm are investigated experimentally. Results demonstrate the effective coupling of light from the liquid filled waveguides to external optical fibers for off-chip detection.

8775-18, Session 4

Special optical fibers and fiber capillaries coated with Indium-Tin-Oxide

Volodymyr Bobuskyy, Jan Mrázek, Ondrej Podrazky, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Indium-Tin-Oxide (ITO) is one of the most widely used transparent semiconductors due to its electrical conductivity and optical transparency. Thin layers of ITO are prepared in industrial scale by a range of physical deposition techniques such as vacuum sputtering etc. Comparing to expensive sputtering techniques a colloidal method of ITO deposition offers cheap, size scalable and continuous technology. The colloidal method allows us to prepare transparent conductive ITO layers on planar substrates. Moreover, combination of the colloidal deposition technique with the optical fiber technology allows us to prepare optical fibers and capillaries coated with transparent conductive layers of ITO. Combination of the transparent conductive layers with waveguiding properties of optical fibers can be exploited in the field of electro-optic sensors and special non-linear devices. This paper deals with preparation of ITO layers from colloidal solutions onto planar substrates, onto optical fibers and into optical capillaries and their characterization.

Commercially available ITO colloidal solution (Sigma-Aldrich) was coated on a set of planar substartes by a dip-coating technique. Deposition parameters such a drawing speed and a concentration of the ITO solution were modified to determined their influence on the thickness of prepared layers. Prepared samples were thermally treated under various atmosphere and temperature. The effects of the treatment to electro-optical properties of prepared samples were analyzed. Deposition and processing parameters were evaluated to achieve minimum resistivity and high transparency of prepared layers. The time-stability of the resistivity of selected samples was observed for three month. The results were compared to those of samples prepared by DC magnetron sputtering and to commercial ITO-coated glasses (Merck). Elaborated methodology was applied to the preparation of optical fibers coated with the ITO layers and to the preparation of capillary optical fibers with inner or outer walls coated with ITO.

The prepared ITO layers exhibit the lowest resistivity after the thermal treatment at 600°C. The presence of oxygen during the thermal treatment improves the optical properties of ITO layers, however, it causes significant increase of their resistivity. The resistivity of samples prepared by the colloidal approach was about two orders higher than of the samples prepared by the DC magnetron sputtering. This resistivity is dependent on the atmospheric humidity. The developed process was succesfully applied to the preparation of special optical fibers and capillaries coated with ITO.

Acknowledgement

The research was supported by The Grant Agency of the Czech Republic, project No. 102/10/2139.

8775-19, Session 5

Dispersion characteristics of plasmonic waveguides for THz waves *(Invited Paper)*

Christos Markides, Frederick Institute of Technology (Cyprus); Charusluk Viphavakit, Frederick Univ. (Cyprus); Christos Themistos, Michael Komodromos, Frederick Institute of Technology (Cyprus); Kyriacos Kalli, Cyprus Univ. of Technology (Cyprus); Anita Quadir, Azizur Rahman, City Univ. London (United Kingdom)

A remarkable expansion of technology to a wide range of components, instruments and applications, carried out in the terahertz portion of the electromagnetic spectrum (loosely defined as the frequencies from 0.3 THz to 10 THz), has been witnesses in recent years. These advances in Terahertz applications depend on the transmission properties of Terahertz sources, the penetration of Terahertz radiation through dielectric materials and the high sensitivity of Terahertz sensors. The unique properties of Terahertz radiation and spectroscopic sensing have lead to new fields of interest and significant advances in astrophysics and atmospheric science, biological and medical sciences, security screening and illicit material detection, non-destructive evaluation (NDE), communications technology, and ultrafast spectroscopy. Terahertz radiation exhibits good balance between good resolution and penetration as well as good selectivity (fingerprint) in many materials.

At present the techniques for generating Terahertz radiation are based on optically pumped lasers (OPTL), time-domain system sources, backward wave oscillators, direct multiplied sources, and frequency mixing. The introduction of quantum-cascade lasers (QCL) has proved more successful for terahertz generation and recently new techniques have revealed that that the performance of terahertz QCLs can be greatly improved by the use of spoof surface plasmon (SP) for active photonic devices.

Moreover significant research is carried out on the development of Terahertz waveguides in order to expand on current applications. Due to the absorption of THz radiation of dielectrics and metals, an outstanding problem has been the development of efficient waveguide structures with minimal transmission loss and minimal dispersion. Several waveguide designs have been proposed, including photonic crystal fibres, cylindrical hollow waveguides with dielectric coating, on-chip terahertz circuits, metallic slit, and microstrip circuits. Among various approaches considered, a metal clad guide which supports surface Plasmon modes (SPMs) is one of the most promising because of low loss in both active components and passive waveguides. Surface plasmon polaritons (SPPs) are electromagnetic waves that propagate along the interface between a metal and a dielectric and decay evanescently on both sides of the interface. They are created because of the resonant interaction of the free electrons of the metal with the electromagnetic field of incident light wave. Recently, it has been shown that a dielectric-coated metal-clad hollow core circular waveguide yields low loss at THz frequencies. Such flexible guides are more suitable to deliver high power electromagnetic waves to a target, instead of using free space transmission.

In the present work the full-vectorial H-field formulation of the finite element Method (FEM) and the finite difference time domain (FDTD) approach have been used to analyse the modal and propagation properties of plasmonic waveguides to investigate the dispersion characteristics of such structures.

8775-20, Session 5

Self-similar pulse shape mode for femtosecond pulse propagation in optical fiber with multi-photon absorption and nonlinear refraction

Vyacheslav A. Trofimov, Irina G. Zakharova, Dmitry A. Smotrov, Lomonosov Moscow State Univ. (Russian Federation); Sheng Lan, South China Normal Univ. (China)

We investigate the mode of laser pulse propagation in homogeneous medium with multi-photon absorption and nonlinear refractivity, at which the shape of pulse is self-similar one along some distance of propagation. Finding the shape of laser pulse with such property is based on the solution of nonlinear eigenfunction problem for Schrödinger equation with nonlinear absorption and nonlinear refraction. Under certain conditions this eigenfunction gives us the pulse shape with requiring properties. We develop also analytical solution of corresponding problem to confirm our computer simulation results.

We showed a possibility of such mode propagation of laser pulse for medium with defocusing refractive index under the condition of presence of multi-photon absorption

8775-21, Session 5

Pressure-driven and other flows in microstructure optical fibres for microfluidics

Paul Christodoulides, G. Florides, Charalambos Koutsides, L. Lazari, Cyprus Univ. of Technology (Cyprus); Michael Komodromos, Frederick Institute of Technology (Cyprus); Frederic Dias, Ecole Normale Supérieure de Cachan (France); Kyriacos Kalli, Cyprus Univ. of Technology (Cyprus)

Microfluidics are important micro-scale devices that can be used to manipulate very small volumes of fluids on the order of nano- to femto-liters. The control and sorting of nano-particles is a primary goal using this technology. There is particular interest in the use of microstructure optical fibers for the transfer of fluids, whereby the guided light interacts with a fluid in the region of the air-hole structure.

We study the fluid transport capabilities of microstructure fibers with cross sections containing circular or elliptical holes, considering the effects of flow rates, fluid viscosity, and the channel diameter. The role of heat flux is considered in relation to the fluid characteristics. We solve the time-dependent Navier-Stokes equations and the convection-diffusion equation. This work is of importance as one cannot assume that the flow dynamics in microstructure fibres will be the same as conventional micro-fluidic channels. Through the study of the heat transfer, for pressure-driven and other flows and for low Reynolds numbers, we confirm anticipated behaviour of the fluids in the micro-channel structure.

8775-22, Session 5

Broadband submicron flattened dispersion compensating fiber with asymmetrical fluoride doped core

Michal Lucki, Richard Zeleny, Czech Technical Univ. in Prague (Czech Republic)

The goal of this paper is to present the progress on Photonic Crystal Fibers designed for specific applications in dispersion compensation. The idea how to restrict chromatic dispersion is to increase the index contrast by using fluoride materials, such as barium fluoride in the first ring of holes, which lower the effective index. In general, fluoride materials compared to standard silica glass in many aspects offer better mechanical and optical properties. The use of fluorides allows achieving broadband dispersion suppression impossible to achieve in standard fibers with similar geometry. The presented result comprises a numerical model of a photonic crystal fiber in a submicron lattice, specific for its negative dispersion coefficient achieved for broad spectrum of telecommunication and infrared spectrum of wavelengths. The core consists of pure silica surrounded by three doped regions and three air-holes. Holes doped with Fluoride materials enhance negative dispersion coefficient to about -420 ps/nm/km. The diameter of doped regions is about 1 micrometer. On the contrary, the diameter of undoped air-holes is responsible for the dispersion slope, which can be interesting for exact slope compensation of standard ITU-T fibers. Simulations were done by using the full-vector FDFD method. The wavelength evolution of refractive index of materials was introduced by using the Sellmeier approximation. The major advantage of the designed fibers is their material composition, low attenuation and broadband utilization.

8775-23, Session 5

Comparison of thermally induced single-mode regime changes in Yb-doped large mode area photonic crystal fibers

Enrico Coscelli, Federica Poli, Riyadh Mwad Naife, Annamaria Cucinotta, Stefano Selleri, Univ. degli Studi di Parma (Italy)

The excellent properties of pulsed Yb-doped fiber lasers, in terms of brightness, beam quality and high doping-level capability, just to mention a few, have earned them a lot of interest by the industry, being an efficient and compact replacement for bulky solid-state or gas lasers in many applications. Power scaling of these systems relies on the possibility to design the active fiber to provide single-mode guiding while preventing the onset of nonlinearities by properly increasing the effective mode area.

The current state-of-art of Large Mode Area (LMA) single-mode fibers is represented by rod-type Double Cladding Photonic Crystal Fibers (DC-PCFs), which nevertheless require a very fine tuning of the design parameters to allow for efficient High-Order Mode (HOM) suppression when the effective mode area increases up to the thousand-?m2 range. Currently, three design approaches appear to be the most viable: the 19-cell core PCF, where the core is obtained by removing the 19 innermost air-holes of the photonic crystal cladding and core down-doping is often used to perform HOM suppression; the Distributed Modal Filtering (DMF) PCF, where HOM filtering is obtained by resonant coupling with high-index elements placed in the cladding; and the Large Pitch PCF (LP PCF), exploiting an “open waveguide” structure to provide an efficient modal sieve to prevent HOM confinement.

Recently, mode-instabilities have been reported to occur in high-power Yb-doped fiber lasers operating beyond a certain power threshold, which depends on the particular fiber employed. Such instabilities are caused by the change of the fiber refractive index profile due to thermo-optic effect which, in turn, allows the propagation of one or more HOMs, not present in the “cold” fiber. As a consequence, further power scaling of fiber laser systems requires the development of fiber designs capable to maintain stable single-mode regime even when a large thermal load is applied in the core.

In this paper the resilience to thermal effects of the different rod-type DC-PCF designs, namely the 19-cell core, the DMF and the LP PCFs, have been compared. A thorough numerical analysis has been performed by applying a full-vector modal solver based on the finite-element method to calculate the guided modes of the PCFs, after obtaining the thermally-induced refractive index change on the fiber cross-section by means of a simple but accurate thermal model. The spectral width and position of the single-mode range have been calculated for each fiber, for different heating conditions, and significantly different properties have been observed. As an example, a blue-shift of the single-mode range has been observed in 19-cell core and DMF PCFs for increasing heat load, while a red-shift has been found in LP PCFs. The causes of the different behavior have been deeply investigated, providing a detailed overview of the influence of thermo-optical effects on the guiding properties of LMA PCFs, as well as some guidelines for the design of LMA PCFs for high-power applications.

8775-24, Session 6

Embedded fibre Bragg gratings in photonic crystal fibres for cure cycle monitoring of carbon fibre reinforced polymer materials *(Invited Paper)*

Camille Sonnenfeld, Vrije Univ. Brussel (Belgium) and Univ. de Caen Basse-Normandie (France); Geert Luyckx, Univ. Gent (Belgium); Francis Collombet, Univ. de Toulouse (France); Yves-Henri Grunevald, Composites, Expertise & Solutions (France); Bernard Douchin, Laurent Crouzeix, Mauricio Torres, Univ. de Toulouse (France); Thomas Geernaert, Sanne Sulejmani, Vrije Univ. Brussel (Belgium); Karima Chah, Univ. de Mons (Belgium); Pawel Mergo, Univ. Marii Curie-Sklodowskiej (Poland); Hugo Thienpont, Francis Berghmans, Vrije Univ. Brussel (Belgium); Sophie Eve, Moussa Gomina, ENSICAEN (France)

Photonic crystal fibres (PCFs) can be optimized for a large range of applications by tailoring the number, the size and position of the air holes that form the confining microstructure around the fibre core. The fabrication of fibre Bragg gratings in their core has been reported several times over the past decade. Standard FBG-based sensors in step-index fibres already present many advantages since they feature small size and low weight they can for example be integrated within composite materials without disturbing the structural integrity. FBG-

based sensors have already proven their ability to measure strain and temperature within composite materials and therefore offer potential to monitor a composite's manufacturing cycle. The performance and quality of a carbon fibre reinforced polymer (CFRP) material highly depends on its cure cycle. Namely, during the cure cycle of CFRP material, residual strains, arising from the difference in thermal expansion coefficient between the resin material and the reinforcement fibres, are built up in the material. The creation of excessive residual strains can result in strength reduction, the appearance of cracks or even lead to delamination. Therefore, there is a growing need of developing sensors which can monitor internal strains during the cure process. So far, integrated FBGs for cure cycle monitoring of CFRP materials only measure longitudinal strain whereas the complete strain field also consists of major strain values in the directions orthogonal to the fibre's axis. Moreover, for these applications high (and by nature inhomogeneous) temperature differences commonly occurs and therefore temperature compensation becomes extremely important at the position of your FBG-based sensor. For large composite structures, it is relatively difficult to determine the temperature at the exact location of the sensor.

In this work, we report on the use of a particular type of highly birefringent PCF to study the cure cycle of a CFRP produced by the vacuum bag autoclave process. The PCF used in this study has been designed in such a way that its phase modal birefringence B exhibits a high transverse strain sensitivity (ten times larger than that reported for highly birefringent conventional fibre). Furthermore, its particular design results in a phase modal birefringence insensitive to temperature changes avoiding the use of obligatory temperature compensation system. A fibre Bragg grating in such a highly birefringent PCF yields two Bragg reflection peaks, one for every orthogonally polarized mode. The wavelength separation between the Bragg peaks is proportional to the phase modal birefringence. By measuring the change of that spectral distance one can perform temperature insensitive transverse strain measurements. In the first part of this study, we demonstrate the possibility to integrate this particular PCF inside a cross-ply composite laminate and monitor its wavelength response for different loading conditions (axial and transversal loadings, and temperature variations). In the second part of this study, two PCFs were embedded in a CFRP part at well-chosen locations during the entire cure cycle of the composite material. We demonstrate on the use of such PCF to obtain insight on the composite cure cycle that would be difficult to detect with any other sensor technology.

8775-25, Session 6

Rocking filters fabricated in side-hole fiber with zero group birefringence

Alicja Anuszkiewicz, Tadeusz Martynkien, Jacek M. Olszewski, Wroclaw Univ. of Technology (Poland); Pawel Mergo, Univ. Marii Curie-Sklodowskiej (Poland); Waclaw Urbanczyk, Wroclaw Univ. of Technology (Poland)

We report on sensing characteristics of the rocking filters fabricated in silica side-hole (SH) fiber with group birefringence crossing zero near l0=1.17 um. This feature of the SH fiber was achieved by placing highly elliptical core doped with 21 mol% of GeO2 in 6.6 um thick glass bridge, which separates two large holes located in the cladding. At longer wavelengths the evanescent field reaches the boundaries of the glass bridge, which results with unusual dispersion characteristic of the phase modal birefringence. As a result, the group modal birefringence crosses zero at l0=1.17 um, while the beat length shows nearly parabolic dependence upon wavelength with maximum at l0 . We present the results of measurement and simulations of the phase and the group modal birefringence in a wide spectral range as well as the polarimetric sensitivity to hydrostatic pressure and temperature in the investigated SH fiber. We also present the transmission and sensing characteristics of the rocking filter fabricated in the SH fiber using CO2 laser. Thanks to almost parabolic dependence of the beat length upon wavelength a broad band (250 nm) coupling between polarization modes was obtained in the rocking filter of a period close to the maximum beat length. For rocking filters of shorter period, the resonances of the same order located on both sides of l0 were observed. As the response of the both resonances has opposite sign, it is possible to double the sensitivity of the rocking filter by applying the differential interrogation scheme. We experimentally demonstrate that in this way the pressure sensitivity of the rocking filter fabricated in the SH fiber can be enlarged to 150 nm/MPa.

8775-26, Session 6

High-sensitivity high-resolution refractometry with twin turn-around-point long-period gratings in a photonic crystal fiber

Jiri Kanka, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

We present the numerical design of a turn-around-point long-period grating in a photonic crystal fiber (TAP PCF-LPG) for high-sensitivity, high-resolution refractometry of gases and liquids. High refractive-index sensitivity is achieved by operating LPGs in the vicinity of the dispersion turning point of the optimized PCF. Despite the resonant wavelength of the optimized PCF-LPG is highly sensitive to the refractive index of analytes, its large shifts could be monitored with a reduced resolution because the resonance dip in the TAP LPG transmission spectrum is broad. To provide also high refractive-index resolution, twin TAP-LPGs have been proposed to be used as 3 dB broadband mode converters in the interferometric scheme. The first LPG couples a portion of the light in the core mode to a forward propagating cladding mode and the second LPG couples the light back to the core mode. The resulting interference fringes within the envelope of LPG attenuation dip provide a means for higher resolution sensing. Instead of monitoring the wavelength shift as a result of a refractive index change, the transmission spectrum can also be analyzed in terms of the shift in phase suffered by the fringe pattern. This is a more accurate way of interpreting the interferometric sensor measurements, since the phase shift is a direct result of an analyte-induced change in optical path length. The designed TAP PCF-LPGs are highly sensitive to variations in PCF-LPG geometrical parameters. The performed numerical simulations and their analysis provide guidelines how to mitigate the adverse effect of possible fabrication imprecision.

8775-27, Session 6

Potential for broad range multiplexing of fibre Bragg gratings in polymer optical fibres and operation in the 700-nm wavelength range

Lutful Khan, Aston Institute of Photonic Technologies Chapter (United Kingdom); David J. Webb, Aston Univ. (United Kingdom); Kyriacos Kalli, Cyprus Univ. of Technology (Cyprus)

Refractive index and structural characteristics of optical polymers are strongly influenced by the thermal history of the material. Polymer optical fibres (POF) are drawn under tension, resulting in axial orientation of the polymer molecular chains due to their susceptibility to align in the fibre direction. This change in orientation from the drawing process results in residual strain in the fibre and also affects the transparency and birefringence of the material (1-3). PMMA POF has failure strain as high as over 100%. POF has to be drawn under low tension to achieve this value. The drawing tension affects the magnitude of molecular alignment along the fibre axis, thus affecting the failure strain. The higher the tension the lower the failure stain will be. However, the properties of fibre drawn under high tension can approach that of fibre drawn under low tension by means of an annealing process. Annealing the fibre can generally optimise the performance of POF while keeping most advantages intact. Annealing procedures can reduce index difference throughout the bulk and also reduce residual stress that may cause fracture or distortion. POF can be annealed at temperatures approaching the glass transition temperature (Tg) of the polymer to produce FBG with a permanent blue Bragg wave-length shift at room temperature. At this elevated temperature segmental motion in the structure results in a lower viscosity. The material softens and the molecular chains relax from the axial orientation causing shrinking of the fibre. The large attenuation of typically 1dB/cm in the 1550nm spectral region of PMMA POF has limited FBG lengths to less than 10cm. The more expensive fluorinated polymers with lower absorption have had no success as FBG waveguides. Bragg grating have been inscribed onto various POF in the 800nm spectral region using a 30mW continuous wave 325nm

helium cadmium laser, with a much reduced attenuation coefficient of 10dB/m (5). Fabricating multiplexed FBGs in the 800nm spectral region in TOPAS and PMMA POF consistently has lead to fabrication of multiplexed FBG in the 700nm spectral region by a method of prolonged annealing. The Bragg wavelength shift of gratings fabricated in PMMA fibre at 833nm and 867nm was monitored whilst the POF was thermally annealed at 80˚C. Permanent shifts exceeding 80nm into the 700nm spectral region was attained by both gratings on the fibre. The large permanent shift creates the possibility of multiplexed Bragg sensors operating over a broad range.

1. Pellerin C, Prud'homme RE, Pézolet M. Effect of thermal history on the molecular orientation in polystyrene/poly (vinyl methyl ether) blends. Polymer. 2003;44(11):3291-7.

2. Dvořánek L, Machová L, Šorm M, Pelzbauer Z, Švantner J, Kubánek V. Effects of drawing conditions on the properties of optical fibers made from polystyrene and poly (methyl methacrylate). Die Angewandte Makromolekulare Chemie. 1990;174(1):25-39.

3. Dugas J, Pierrejean I, Farenc J, Peichot JP. Birefringence and internal stress in polystyrene optical fibers. Applied optics. 1994;33(16):3545-8.

4. Jiang C, Kuzyk MG, Ding JL, Johns WE, Welker DJ. Fabrication and mechanical behavior of dye-doped polymer optical fiber. Journal of applied physics. 2002;92(1):4-12.

5. Johnson IP, Webb DJ, Kalli K, Yuan W, Stefani A, Nielsen K, et al., editors. Polymer PCF Bragg grating sensors based on poly (methyl methacrylate) and TOPAS cyclic olefin copolymer2011: SPIE.

8775-28, Session 6

Simultaneous measurement of liquid level and temperature using non uniform grating

Dipankar Sengupta, M. Sai Shankar, Srimannarayana Kamineni, National Institute of Technology, Warangal (India)

The present work proposes a sensor head design making use of non uniform fiber Bragg grating for simultaneous measurement of liquid level and temperature eliminating usage of two separate FBGs. The sensing technique follows with a cantilever and a bouyancy tube is connected to the free end of the cantilever. A non uniform grating is prepared by chemical etching. As a result of chemical etching, the reflection peak of the FBG splits into two, corresponding to the two halves of the grating. The etched part of FBG is not in contact to the cantilever and will not experience any strain due to the deflection of the cantilever. The un-etched part of the FBG is sensitive to the axial strain as well as to temperature and the etched part of the FBG which is not in contact with the cantilever is sensitive to temperature only.

As the liquid level present in the tank raises the buoyancy force on the buoyancy tube increases as a result the FBG experience a different strain due to change in diameter of two half part of the FBG. The liquid level sensitivity of the un- etched part of the FBG is calculated for a change in liquid level upto 30cm and is 16pm/cm. The temperature sensitivities of etched and unetched part of the FBG is 9pm/0C.

The independent measurement of sensitivity coefficient of liquid level and temperature of etched and unetched FBG is useful for writing them in matrix form that can yield the detection of liquid level and temperature.

8775-29, Session 6

Thermoluminescence characteristic of flat optical fiber in radiation dosimetry under different electron irradiation conditions

Alawiah Ariffin, Multimedia Univ. (Malaysia); Sabar Bauk, Univ. Sains Malaysia (Malaysia); Hairul Azhar Abdul Rashid, Multimedia Univ. (Malaysia); Nizam Tamchek, Univ. Putra Malaysia (Malaysia); Faisal Rafiq Mahamd Adikan, Univ. of Malaya (Malaysia); Khairul Anuar Mat Shariff, Mohd. Imran Zulkifli, Shahrin Zen Muhammad Yasin, Telekom Research and Development (Malaysia); Ghafour Amouzad Mahdiraji, Univ. of Malaya (Malaysia); Wan Saffiey Wan Abdullah, Malaysian Nuclear Agency (Malaysia); Zulfadzli Yusoff, Mohd. Ridzuan Mokhtar, Multimedia Univ. (Malaysia); David Bradley, Univ. of Surrey (United Kingdom); N. M. Noor, Univ. Putra Malaysia (Malaysia)

Thermoluminescence (TL) flat optical fibers (FF) have been proposed as radiation sensor in medical dosimetry. Kinetic parameters and dosimetric glow curve of TL response were studied in FF with respect to electron irradiation of 6 MeV, 15 MeV and 21 MeV using linear accelerator (LINAC) in the dose range of 2.0-10.0 Gy. The proposed FF shows excellent linear radiation response behavior within the clinical relevant dose range for all of these energies, good reproducibility, independence of radiation energy, independence of dose rate and exhibits a very low thermal fading. From these results, the proposed FF can be used as radiation dosimeter and favorably compares with the widely used of LiF:MgTi dosimeter in medical radiotherapy application.

8775-30, Session PS

Radiation dose to radiosensitive organs in pet myocardial perfusion examination using versatile optical fibres

Salasiah Mustafa, Muhammad Hishar Hassan, Abdul Jalil Nordin, Fathinul Fikri Ahmad, Nizam Tamchek, Univ. Putra Malaysia (Malaysia); Hairul Azhar Abdul Rashid, Multimedia Univ. (Malaysia); Noramaliza Mohd Noor, Univ. Putra Malaysia (Malaysia)

Cardiac positron emission tomography (PET) provides an accurate means for diagnosing obstructive coronary artery disease (CAD), which appears superior to single photon emission tomography (SPECT) especially in the obese and in those undergoing pharmacologic stress. The ability to record changes in left ventricular function from rest to peak stress and to quantify myocardial perfusion (in mL/min/g of tissue) provides an added advantage over SPECT for evaluating multivessel CAD. However, the radiation dose to the radiosensitive organs is a public health concern. The study aims to estimate radiation dose to radiosensitive organs of patients who undergoing PET myocardial perfusion examination at Centre for Diagnostic Nuclear Imaging, Universiti Putra Malaysia during one month period using optic fibres. All stress and rest paired myocardial perfusion PET scans will be performed with the use of 82-Rubidium (Rb-82). The optic fibres will be taped to the eyes, thyroid and breasts of patients prior to the infusion of Rb-82, to accommodate the ten cases for the rest and stress PET scans. The results will be compared with established thermoluminescence material TLD-100 chips. All data will be analysed to estimate the radiation dose to the radiosensitive organs using one-way ANOVA. A p value of <0.05 was considered significant.

8775-31, Session PS

Double-clad rare-earth-doped fiber with cross-section tailored for splicing to the pump and signal fibers: analysis of pump propagation

Pavel Koska, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Pavel Peterka, Ivan Kasik, Vlastimil Matejec, Ondrej Podrazky, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

Rare-earth doped fibers device are capable to generate high-power high-quality beams thanks to optical pumping in the so-called double-clad fibers. In such rare-earth-doped double-clad fibers, the low-brightness beam of semiconductor lasers is converted into high-brightness beam. Highest power is usually achieved in master-oscillator power-amplifier (MOPA) configuration. In the MOPAs, special components for combination of the pump and signal are needed and these components have inevitable insertion losses. Despite these losses are low, of the order of 1 dB, for high power operation these

losses might be an issue. Recently, we demonstrated the double-clad fiber of novel design where no combining element is necessary and the insertion losses can be significantly minimized. The cross section of the double-clad fiber is tailored for splicing two round fibers, one for the pump and the other for the signal.

In this contribution we present numerical study of propagation of the multimode pump radiation in the inner cladding of the developed double-clad fiber. Field evolution was simulated using full vector finite element beam propagation method. Curvature and twist of the fiber is involved in the model. To save the time of the numerical simulations, the twist is simulated also by skewed pump input beam. Flat-top field profile was introduced into the half of the structure with predefined inclination angle of 4 degrees. The longitudinal dependence of power distribution was then analyzed. The simulations showed that after the length of propagation of about 40 mm, the ratio of the fractional pump power contained in the rare-earth-doped core corresponds to the ratio of the area of the rare-earth-doped core to the area of the whole fiber cross section. It confirms that homogeneous power distribution in the structure is established in reasonably short distances from the pumping end of the fiber. The results of simulations confirm suitability of the tailored cross section for effective pump absorption along the rare-earth doped fiber.

The authors gratefully acknowledge the financial support by the Czech Ministry of Education, Youths and Sports for the project 'FILA' (ME10119), and the Ministry of Industry and Trade, project 'EYESAFE2u' (FR-TI4/734).

8775-32, Session PS

Compositional and structural dependence of chromatic dispersion in tellurite microstructured optical fibers

Zhongchao Duan, Hoang Tuan Tong, Meisong Liao, Dinghuan Deng, Takenobu Suzuki, Yasutake Ohishi, Toyota Technological Institute (Japan)

Control of chromatic dispersion in optical fibers is a very important issue for communication systems, in both the linear and the nonlinear regimes, and for any optical system supporting ultra-short soliton pulse propagation. In this work, we highlight the dependence of chromatic dispersion on refractive index distribution and show some guidance of dispersion design in highly nonlinear microstructured optical fibers. The chromatic dispersion and loss of fundmential mode are studied using a fully vectorial finite difference method (FV-FDM). The total dispersion of fiber is composed of two components, a material dispersion and waveguide dispersion. The former is mainly dependent on material composition of core glass. And the waveguide dispersion of fiber mainly depends on refractive index distribution in cross-section. The radial step of refractive index produces a peak in waveguide dispersion curve whose value and position are related to both contrast of refractive index and its position. For step index fiber, the peak of waveguide dispersion decreases and shifts to long-wavelength with core size increasing, whereas it increases and shifts to long-wavelength with refractive index contrast increasing. In the case of microstructured optical fiber, i.e. fibers with air hole cladding, the pitch and diameter of air hole define the refractive index contrast and consequently determine the waveguide dispersion. By manipulating the waveguide dispersion, chromatic dispersion can be tailored freely to shift zero dispersion wavelength or flatten the profile. Furthermore, employing more refractive index differences, viz. claddings, air hole rings, more dispersion peaks can be obtained in waveguide dispersion. The dispersion peak can be controlled separately by adjusting corresponding refractive index contrast. This feature makes the design of chromatic dispersion much efficient and flexible in highly nonlinear optical fiber. Finally some particular dispersion profiles such as all-normal-dispersion, ultra-flattened and zero dispersion, multi zero dispersion wavelength and so on are designed within W-type fiber, photonic crystal fiber and hybrid microstructured fibers. The propagation loss and cutoff of wavelength are also studied and compared between different types of fibers.

8775-33, Session PS

Measurement of chromatic dispersion and dispersion slope of fiber using a supercontinuum source

Miroslava Kadulová, Petr Hlubina, Technical Univ. of Ostrava (Czech Republic); Ryszard R. Buczynski, Univ. of Warsaw (Poland)

A spectral interferomery-based method [1] to measure the chromatic dispersion, the zero-dispersion wavelength and the dispersion slope of a fiber is presented. This technique utilizes an experimental configuration with a supercontinuum source in combination with a dispersion-balanced Mach-Zehnder interferometer [2]. A low-resolution spectrometer is employed at the output of the setup to record a spectral interferogram for the path length adjusted in the interferometer.

The spectral interferograms are resolved in the vicinity of a stationary phase point corresponding to a specific equalization wavelength at which the visibility of spectral interference fringes is the highest. First, from a series of spectral interferograms the dependence of the equalization wavelength on the adjusted path length is obtained. The measured dependence of the path length difference on the equalization wavelenth is used to determine the dispersion of the differential group index of the fiber. Next, the chromatic dispersion, including the zero-dispersion wavelength, is determined exploiting a least square fitting. Finally, the dispersion slope is obtained. The technique has been applied for measurement of dispersion characteristics of specialty optical fibers, including highly nonlinear suspended core fiber.

[1] P. Hlubina, D. Ciprian, and M. Kadulová, Measurement of chromatic dispersion of polarization modes in optical fibres using white-light spectral interferometry, Meas. Sci. Technol. 21, 045302, 2010.

[2] P. Hlubina, M. Kadulová, and D. Ciprian, Spectral interferometry-based chromatic dispersion measurement of fibre including the zero-dispersion wavelength, J. Europ. Opt. Soc. Rap. Public. 7, 12017, 2012.

8775-34, Session PS

Broadband dispersion decreasing photonic crystal fiber for compression of optical pulses

Richard Zeleny, Michal Lucki, Czech Technical Univ. in Prague (Czech Republic)

Adiabatic soliton compression is an effective method for compression of optical pulses narrower than 10 ps. Soliton duration is reduced if nonlinearity or group velocity dispersion is slowly varied, while maintaining the soliton energy. In particular, high compression ratios can be obtained by propagating of optical radiation through the entire length of a dispersion decreasing fiber. Therefore a novel photonic crystal fiber is designed and studied in this paper. The fiber is characterized by the silica core surrounded by nine rings of air-holes, where hole-sizes of the two innermost rings are reduced. In order to obtain the wavelength dependence of the effective refractive index, finite difference frequency domain method is employed. The calculated anomalous dispersion is flat from 1250 to 1700 nm at the fiber input, and therefore the photonic crystal fiber can be used at a desired wavelength in this range. Chromatic dispersion of the fiber is decreased concurrently with the fiber effective mode area, in comparison to other studies. Consequently, the fiber nonlinear coefficient is increased and compression ratio is enhanced. This is due to, the diameter of air-holes of the innermost ring being linearly reduced along the fiber length. The compression factor is theoretically calculated at the wavelengths of 1300, 1310, 1400, 1550 and 1700 nm. In the ideal case, the factor up to 120 times for the first-order soliton at 1550 nm is achieved primarily by dispersion being changed from 100 to 1 ps/(nm?km) at the considered wavelength. Higher compression ratio can be reached with the initial soliton order $1< N<2$. Moreover, the minimum fiber length required can be shortened, while adiabatic condition is satisfied. Finally, the designed fiber could eventually be fabricated in the stack and draw process and further used as a part of optical pulse compression method.

Conference 8776: Holography: Advances and Modern Trends III

Monday - Tuesday 15–16 April 2013

Part of Proceedings of SPIE Vol. 8776 Holography: Advances and Modern Trends III

8776-1, Session 1

Two-wavelength volume holographic recording in thick phenanthrenequinone-doped poly(methyl methacrylate) photopolymer *(Invited Paper)*

Ken-Yuh Hsu, June H. Lin, Shiuan Huei Lin, National Chiao Tung Univ. (Taiwan)

Holographic recording via two-wavelength process, in which the hologram is recorded at chosen volume with one wavelength laser beam by use of a uniform gating illumination with another wavelength light simultaneously, has many unique features over conventional single-wavelength holographic recording. This technique can be considered as an optical fixing of hologram and provides applications using materials with abilities of spatial and temporal controls of selective recording as well as nondestructive readout before the recording medium reaches saturated. One of particularly successful applications is optical fixing of photorefractive hologram in doubly-doped LiNbO3 crystals for the holographic data storage, which attracts intensive research efforts in the field of optical information during the past decades [1].

The first experimental demonstration of two-wavelength holography in photopolymer was made by G. C. Bjorklund et al. in 1982 [2], who proposed to utilize a ?-diketone moiety for performing two-wavelength photochemical recording. They successfully demonstrated holographic recording with 11% diffraction efficiency in a 400 ?m thick biacetyl dissolved poly-cyanoacrylate film by using an ultraviolet gate light and write laser at 752 nm. More recently, we demonstrated experimentally that two-wavelength holographic recording has also been achieved in a 2-mm thick phenanthrenequinone-doped poly (methyl methacrylate) (PQ/PMMA) photopolymer [3]. The wavelength of gating light is 325 nm and the one of the recording light is at 647 nm. The hologram showed excellent volume Bragg grating properties. However, the diffraction efficiency was only 5%, which may not be enough for some applications. In order to improve holographic characteristic of these materials, it will be powerful to have theoretical modeling of two-wavelength holographic recording in such photopolymers. In this paper, based on the four energy level scheme and the photochemical mechanism of ?-diketone moiety, we propose theoretic modeling of the photochemical kinetics of cascaded two photon absorption effects in PQ/PMMA photopolymer. At the same time, applying this model to recording configuration, the two-wavelength holographic recording kinetics can then be theoretic simulation. It provides a rule to guide two-wavelength recording and optimize holographic characteristics in PQ/PMMA photopolymer. In addition, we also present experimental studies on two-wavelength holographic recording in 2-mm thick PQ/PMMA photopolymer. The characteristics including plane-wave holographic recording and nondestructive readout, are presented.

[1] A. Adibi, K. Buse, D. Psaltis, “Two-center holographic recording,” J. Opt. Soc. Am. B, vol. 18(5), pp. 584-601, 2001.

[2] C. Brauchle, U.P. Wild, D.M. Burland, G.C. Bjorklund, D.C. Alvarez, “2-Photon Holographic Recording with Continuous-Wave Lasers in the 750-1100-Nm Range,” Opt. Lett., vol. 7(4), pp. 177-179, 1982.

[3] P.L. Chen, S.L. Cho, J.H. Lin, S.H. Lin, K.Y. Hsu, C. Sien, “Two-wavelength holographic recording in thick phenanthrenequinone-doped poly(methyl methacrylate) photopolymer,” Opt. Eng., vol. 51(3), p. 030503, 2012.

8776-2, Session 1

Holographic recordings with high beam ratios on improved Bayfol(R) HX photopolymer

Günther Walze, Horst Berneth, Friedrich-Karl Bruder, Thomas Fäcke, Rainer Hagen, Dennis Hönel, Thomas Rölle, Marc-Stephan Weiser, Bayer MaterialScience AG (Germany)

Bayfol® HX is a new class of recording materials for volume holography. It was first introduced in 2010 and is offering the advantages for full-color recording and moisture resistance without any chemical or thermal processing, combined with low shrinkage and detuning. These photopolymers are based on the two-chemistry concept in which the writing chemistry is dissolved in a preformed polymeric network. This network provides the necessary mechanical stability to the material prior to recording.

In addition to the well-known security and imaging applications, Bayfol® HX also offers a new opportunity for the manufacturing of volume Holographic Optical Elements (vHOE’s) in new optical and optoelectronic applications. For the development of functional layouts and associated holographic recording schedules for these HOEs a detailed knowledge of the material properties is necessary.

In this paper we describe a method to simulate the writing mechanism for the Bayfol® HX photopolymer. The model is investigated experimentally by recording and evaluation of specifically designed directional diffuser HOEs as they would be used e.g. for light shaping or light management purposes. One important observation is the capability of the material to form diffraction gratings even with very high intensity ratios of recording beam versus reference beam. Covered in this evaluation are different photopolymer product variations, including development grades with improved bleaching properties and increased dynamical range, which enable simultaneous multi-color recording while keeping a high diffraction efficiency.

8776-3, Session 1

Convertible holograms in calcium fluoride crystals with color centers

Alexander E. Angervaks, Alexander S. Shcheulin, Alexander I. Ryskin, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

The photochromy of additively colored (reduced at heating in a Ca vapor) calcium fluoride crystals containing color centers is based on the photo-induced transformation of the center type. The centers are subdivided into “simple” centers, which are composed of 1–4 anion vacancies with an equal number of electrons and highly aggregated centers. The highly aggregated centers are then subdivided into “colloidal” centers, two-dimensional metal inclusion embedded into the crystal lattice, which include thousands of anion vacancies/electrons, and “quasi-colloidal” centers of unknown composition and structure. It is likely that they are in an intermediate position by the number of these components between simple and colloidal centers. In hologram recording, simultaneously with center type conversion, their space redistribution in the sample volume takes place. The color centers located at the maxima of the fringe pattern are photo-ionized, leave the maxima and concentrate in the ranges of the minima of the pattern. The greater the exposure, the narrower are the regions where color centers concentrate, and the more their spatial distribution deviates from the distribution of intensity in the fringe pattern being recorded. Thus, an exposure-dependent hologram profile differs from the sinusoidal one. The peculiar diffusion-drift mechanism of the recording is responsible for the extremely high hologram stability to both heating and illumination of the sample with a hologram by the non-coherent radiation. However, the post-exposure photo-thermal treatment of the sample with the hologram with using such radiation results in the partial or total transformation of the center type and some modification in their space distribution. Thus, keeping the hologram, such treatment influences its diffraction efficiency and profile. It can be used for fabrication of up to 10 mm in thickness and high-stable holograms at reading out in both visible and infrared ranges of the spectrum.

8776-4, Session 1

Ruthenium and Rhodium doped sillenite crystals: holographic properties and applications at near-infrared spectral range

Vera M. Gospodinova, Ken-Yuh Hsu, Shiuan Huei Lin, Ren C. Liu, Yu H. Lin, National Chiao Tung Univ. (Taiwan)

Real-time holographic recording and an improvement of the response time in Rh-doped Bi12TiO20 (BTO) and Ru-doped Bi12SiO20 (BSO) sillenite crystals at 1064 nm are reported. By using pump green light as pre-exposure significant operation response speed of 20 ms is achieved in Rh-doped BTO and 50 ms in Ru-doped BSO. Furthermore, a possibility to prolong the holographic grating lifetime by combining two-wavelength recording is demonstrated in Ru-doped BSO. The experimental results are supported by numerical simulation analysis, suggesting two different traps involved in the space-charge transport mechanism. Quasi-permanent storage of an image with fast updating speed using low intensity operation at near-infrared is performed. The presented results show perspective future of the studied materials for further applications in real-time image processing and non-destructive bio-objects testing.

In addition, an opportunity to implement Rh- or Ru doped sillenite crystal with liquid crystal cell into a hybrid organic/inorganic device (optically addressed modulator) working at near infrared spectral range is demonstrated, which opens many perspectives for advanced near infrared applications.

8776-5, Session 1

Investigations of the behavior for PQ-PMMA material post-exposure

Yue Qi, H. Li, Univ. College Dublin (Ireland); Elen Tolstik, Friedrich-Schiller-Univ. Jena (Germany); Jinxin Guo, Univ. College Dublin (Ireland); Michael R. Gleeson, National Univ. of Ireland, Maynooth (Ireland); V. Matuevich, Richard M. Kowarschik, Friedrich-Schiller-Univ. Jena (Germany); John T. Sheridan, Univ. College Dublin (Ireland)

In order to investigate the photopolymer material in a better way, it is very necessary to understand the behavior of different photosensitizers in the material. Several studies of the time varying photon absorption effects, which occur during the photoinitiation process involving in photopolymer materials, have been presented, including the process of: (i) the photosensitizer absorption, (ii) photosensitizer recovery, and (iii) photosensitizer bleaching. Based on an analysis of these mechanisms, the production of primary radicals can be physically described and modeled. In this paper we estimate the key dye parameters values of the photosensitizers, (i.e., molar absorptivity, ?, quantum efficiency of the reaction, ?, recovery rate, kr, and bleaching rate, kb), and the related simulation work has been done as well. To avoid the complexities involved in estimating the rate constant of intersystem crossing, kst, in going from the excited singlet state photosensitizer to the excited triplet state photosensitizer, we introduce two rates, kaS and kaT, they are the proposed rate constants of photon absorption in going from the ground state to the singlet and triplet states, respectively. Using the resulting model, four kinds of Xanthene dyes: Erythrosin B; Eosin Y; Phloxine B, Rose Bengal, and one Thiazine dye: Methylene Blue, are experimentally characterised for use in an AA/PVA photopolymer.

8776-6, Session 2

Numerical analysis of volume holograms with spherical reference wave based on Born approximation

Shuhei Yoshida, Manabu Yamamoto, Tokyo Univ. of Science (Japan)

Holographic Data Storage (HDS) is one of the next generation storage technologies that can actualize high data capacity and high data transfer rate. Since information is recorded 3-dimensionally in a thick medium, data capacity of the HDS is not constrained by diffraction limit. However, behavior of wavefront in an inhomogeneous thick medium is highly complex, and it is hard to handle propagation of wavefront in the medium analytically. Therefore, we establish a numerical technique for analysis of volume holograms. The proposed technique is based on the scalar diffraction theory, which is described as the volume integral equation. By applying Born approximation and angular spectrum method to the volume integral equation, the technique can be applicable for various problems. We analyze characteristics of the volume hologram with spherical reference wave, and confirm effectiveness of the proposed technique.

Conventionally, coupled mode theory such as coupled wave analysis (CWA) and rigorous coupled wave analysis (RCWA) are widely used for the analysis of diffraction characteristics in thick media. Especially, CWA can evaluate diffraction efficiency easily by using analysis formula. However, CWA cannot handle complex grating such as a volume hologram with spherical reference wave. And there is a limit to RCWA, which come from coupled mode theory. Finite-difference time domain (FDTD) method and beam propagation method are also used for analysis of thick gratings. These methods are based on Maxwell's equations. In order to formulate FDTD method and BPM, Maxwell's equations are discretized in the time and frequency domain, respectively. FDTD method and BPM can deal in intricately-shaped gratings; therefore, these methods are suitable for analysis of volume holograms. Though, FDTD method requires huge computer resources, and BPM have trouble analyzing reflection type holograms because of some approximations. Compared to above-mentioned techniques, the proposed technique has application potentiality for various problems, and it is easy to implement.

In this study, we show effectiveness of the proposed technique by applying to analysis of the volume hologram with spherical reference wave. It can be expected that the proposed technique may become a tool for design of HDS systems.

8776-8, Session 2

Optimization of holopixel size and perspectives number in holographic stereogram

Alexander Y. Zherdev, Sergey B. Odinokov, Dmitriy S. Lushnikov, Vladimir V. Markin, Bauman Moscow State Technical Univ. (Russian Federation)

The mathematical modeling of signal conversion process by holographic optical elements (HOE) in holographic stereogram is advanced. Expression for the HOE point spread function (PSF) in the obser's plane is obtained and discussed. The relationship between observation distance, HOE size, and perspectives number is disclosed. The approach of optimized perspectives number is suggested.

In the final part of the article the limitations and prospects of the holographic stereograpm technology in artistic and security holography are analyzed.

The holographic stereogram (HS) is a stereogram, in which parallax-panoramagram is decoded by holographic optical elements (HOE) called holopixels. The properties of recorded HOE fully define the quality of 3D image, displayed by HS. This article is devoted to mathematical modeling of holopixel and its signal conversion process.

The canonical scheme of obtaining the HS is considered. In this scheme the parallax-panoramagram displayed on screen is an input signal; and the image of parallax-panoramagram projected on observer's plane is output signal. The consideration carried out with two assumption. First, no one method of spectrum blurring is used. Second, the hologram has an ideal transfer function. In conversion process the image suffers a blur because of HOE point spread function (PSF).

Besides the effect of curtains in HS is considered. The digital nature of HS causes the digital nature of the its 3D image. An observer percepts the image as composing of a number of plane images. That planes separated by unequal distances.

This blur limited the maximum perspectives number of HS. From the other side the observer's pupil size limited the minimum perspective number.

The mathematical modeling shows, that HOE PSF depends on various parameters including wavelength, HOE aperture size, and observation distance. This allows us to carry optimization of HS related parameters, such as HS perspective number and HOE size for given observation distance. In different artistic and security uses this optimization must be carried out in different way.

8776-10, Session 3

Security holograms employing perspectival anamorphosis and stereoscopy

Ivo Aubrecht, Police presidium CR (Czech Republic)

Perspectival anamorphosis is an artwork technique, which requires the viewer to occupy a specific vantage point to see the correct image. Stereoscopy is a method of creating illusion of spatiality from a pair of images for the left and right eyes, which requires the viewer to percept each of the images only with the corresponding eye with use of a device, such as a stereoscope viewer, special glasses or a lenticular foil. Capability of capturing spatial scenes and specific geometry of observation/ illumination for correct interception of 2D or 3D image information are both inherent to holography, without the need of whatever viewing equipment.

Security holograms, or better to say diffractive optically variable image devices (DOVIDs), have been employed for documents and goods to guarantee authenticity since 1980's. More and more complex DOVIDs have been being devised and ever more sophisticated and demanding technologies have been being used in production of them. Yet, passable counterfeits have been appearing still. Therefore, calls for DOVID designs facilitating easy practical authentication that ordinary people are capable of are understandable. However, requirements on easiness to authenticate and immunity against mimicking may go against each other, and a compromise has to be sought for.

This paper suggests employment of holography, stereoscopy and perspectival anamorphosis in synergetic combination. The goal is a security element which can be authenticated without the use of a special device and which, owing to the combination of the tree techniques, compels attentive inspection.

8776-11, Session 3

Correlation method for quality control of master matrix used to embossing a security holograms

Vasily Kolyuchkin, Alexander Y. Zherdev, Bauman Moscow State Technical Univ. (Russian Federation); Evgeny Y. Zlokazov, National Research Nuclear Univ. MEPhI (Russian Federation); Dmitriy S. Lushnikov, Sergey B. Odinokov, Bauman Moscow State Technical Univ. (Russian Federation); Andrey V. Smirnov, Krypten (Russian Federation)

Nowadays there is a widespread the hot embossing technology used to manufacture of security holograms. Security holograms quality depends on master matrix perfection used in the technology of hot embossing replication. Master matrix quality control reduces the rejection rate of security holograms production before them manufacturing. That allows saving company's time and money.

Relief parameters are among the determining factors affecting the quality of the hologram. The paper offers the correlation method to control the quality of the security hologram master matrix by analyzing their images in the spatial frequency domain. The essence of the correlation method is to calculate the two-dimensional correlation function between the Fourier spectrum of controlled master matrix image and the Fourier spectrum of an image used as a reference sample. The correlation method has several advantages in problem solving of classifying of objects according to their images. First, the correlation between the two functions can be calculated using the fast Fourier transform algorithm. Second, the uses of invariant correlation filters are capable of providing distortion-invariant pattern recognition or classifying.

To achieve invariance of the algorithm to the variations of registration conditions the correlation filters are used, which the impulse response is a linear combination of training images. In the capacity of the training pattern both the images of the good master matrix and the bad master matrix are used. The paper describes the composite correlation filter known as Maximum Average Correlation Height filter (MACH). The idea of the filter is based on a maximization of the correlation peak average height and a minimization a standard deviation of the peak shape to the optimal one.

The paper presents the optoelectronic device for master matrix quality control. The device includes a digital microscope recording images with television camera, a device for linear movement, a lighting system and a computer. This device allows to register an image of the master matrix. The correlation algorithms of master matrix quality control are implemented at the computer. The method has been tested by the real samples of master matrix. Experiments conducted by the device have given encouraging results. Based on these studies, it was concluded that the invariant correlation algorithm can be used to determine the master matrix quality.

8776-13, Session 3

Digital holographic encryption with multiple-key encoding using micro phase-shifting interferometry

Chi-Ching Chang, MingDao Univ. (Taiwan); Min-Tzung Shiu, National Defense Univ. (Taiwan)

This research uses optical interferometry and digital image processing technique to capture, via coaxial architecture and within the CCD resolution limit, the holographic information of the object beam and the encryption key. The encryption can be completed using the computer generated holograms with multiple keys that include 1) the amplitude and the phase distribution of the primary encryption key, 2) the reconstruction distance of the image, 3) the elimination of zero-order term, and 4) the phase value modulated via arbitrary micro phase-shift interferometry.

This study has shown that the decryption is not achievable without a primary key. The encrypted image can be transmitted to and captured by a CCD at the receiving end, and then decrypted via simple logical operations. The autocorrelation between the original and the decrypted images shows 100% similarity. The decrypted 3D image can be displayed via the holographic display technology. Having the integrity that is comparable to that of traditional optical holographic encryption, this technique has the convenience and simplicity of digital holographic processing and thus provides a secured solution for holographic information transmission.

8776-14, Session 4

Digital holography for recording of incoherent-object hologram as complex spatial coherence function

Dinesh N. Naik, Giancarlo Pedrini, Wolfgang Osten, Univ. Stuttgart (Germany)

We propose and demonstrate the recording of hologram of an incoherently illuminated object by using a Sagnac radial shearing interferometer, a Pockels cell and an 8 bit CCD camera. Since the invention of on-axis holography by Gabor, various attempts have been made to record hologram of an incoherently illuminated or self-luminous object. The pioneering ideas came from Mertz and Young and later from Lohmann. These ideas were followed by a variety of experimental geometries that enables one to record the hologram of an incoherent object. Generally, in incoherent holography, a copy of such an object is made with the help of an appropriate interferometer. The light emitted by each point on the object could interfere only with its counterpart in its copy. The hologram of the incoherent object is an intensity distribution resulting from the incoherent addition of from the interference of the field from each point of an incoherently illuminated object with its counterpart from the copy. The reconstruction of such a hologram is being done in a similar fashion as in coherent –light holography by physically illuminating it with coherent light. The above mentioned ideas of incoherent holography were conceived after the invention of coherent-light holography and their concepts seems indirectly related to it. However, in the proposed technique, an approach based on statistical optics is used for understanding the concept of recording of an incoherent-object as complex spatial coherence function. Its principle is based on van Cittert Zernike theorem according to which the spatial coherence function measured at far-field from an incoherent source is proportional to the Fourier transform of the source's planar intensity distribution. The Sagnac radial shearing interferometer is used for the correlation of optical fields and the Pockels cell is used to shift the phase of the interfering fields. Due to common-path geometry of the interferometer, it is insensitive compared to the conventional PZT-based mechanical mirror movement. The Pockels cell introduces a phase difference between the orthogonally polarized radially sheared beams at the output of the interferometer. The fringe contrast and fringe phase that jointly represent the complex spatial coherence function are measured by applying a 5-step phase shifting algorithm while recording the interferograms. The results of recording and reconstruction of an object illuminated using a light emitting diode, Luxeon Star LXHL-MMID, having spectral width at half maximum of about 35nm at wavelength 530nm are presented. Due to the implementation of the phase shift by using a Pockels cell, the system is mechanics free and has the potential for automated fast measurement which can be applied for the investigation of dynamic situations. Moreover, the interference of the optical field even with low temporal coherent light is achieved without using any interference filter and a reliable 3-D object reconstruction can be achieved even in an outdoor environment due to the inherent stability provided by the common path interferometer. By changing the shearing parameter, we can tailor the range of the measured coherence function depending on object under test. This could enable one to use it as coherence zooming microscope.

8776-15, Session 4

Holographic nanointerferometer with digital magnification

Vladimir Y. Venediktov, Sergey A. Pulkin, Irina M. Pasechnik, St. Petersburg Univ. (Russian Federation)

The method of holographic interferometry with increasing sensitivity was applied for measurements of height of nano-steps (from 10 nm and higher) with standard uncertainty about 0.5 nm. The initial microinterferogram with fringes of equal thickness is obtained in Michelson micro-interferometer with nano-step sample in one of arms. That interferogram is registrated on CCD – camera and digital inteferogram passed on matrix phase modulator with spatial resolution 30 lines/mm. The matrix phase modulator is placed on the exit of two-beam Mach-Cender interferometer and illuminated by two plane laser beams. These two beams are diffracted on phase modulator, are focused on and filtrated by diaphragm with holes in (+ 1-st) and (– 1-st) order of diffraction. The second digital interferogram with twice increasing sensitivity is obtained on CCD – camera and so on. The increasing of sensitivity is obtained because interference of waves with complex conjugated phases. One can obtain the interference of higher orders too if work with nonlinear interferogram. It is possible to made any carrier fringe space frequency because usage of two plane waves in interferometer. The flatness less than ?/100, topography of surfaces with height difference less than few nanometers is possible to research with increased sensitivity too. Also we demonstrate the possibilities of Rozhdestvenski Hook method with increasing sensitivity for measuring of oscillator strengths (transition probabilities) for weak atomic transitions. It is important for future development of interference spectroscopy because usual hook method has insufficient sensitivity and allows us to measure oscillator strengths only for resonant transitions from ground state or from metastable states for strong transitions. It's necessary to underline, that holographic interferometric methods with increasing sensitivity are well known but here we demonstrate the possibility of these methods with using of digital interferograms registered on matrix phase modulator.

8776-16, Session 4

Optical system, comprising digital holographic display and humane eye

Vladimir Y. Venediktov, St. Petersburg Univ. (Russian Federation)

The problem of holographic display, providing real 3D imaging of real or imaginary objects by means of holographic reproduction, has a long story of discussion and in-vestigation. Recently the technique was strongly pushed forward by arrival on the market of the computer-controlled liquid crystal matrix phase arrays. Such elements, in particular that of HOLOEYE Photonics AG (http://www.holoeye.com/) production provide the possibility to record efficient thin phase holograms.

Optimization of holographic display performance requires account for the human eye properties, i.e. limited size of its pupil and its position with respect to the display.

We report first results of laboratory testing of such a system prototype (see Fig-ure). We have used the transmission type element Holoeye LC-2002 (600x800 pix-els, 21x26 mm clear aperture). It was illuminated by the collimated plain beam of He-Ne laser (633 nm). The computer hologram has reconstructed the virtual (imaginary) image, which was observed by experimentator eye, positioned at the distance ~1500 mm from this image. For recording the image we have used the high-quality profes-sional digital camera, whose lens pupil size was manually controlled.

The structure of hologram was calculated with the use of the proprietary code with account for the real human (or photographic lens) pupil diameter of 3-4 mm. From the optical point of view this pupil has served as a field aperture, extracting from the overall diffracted field the proper image, predetermined for observation by eye in this position. The experiments have confirmed the expected behavior of the system.

8776-17, Session 4

Holographic in-line imaging setup for measuring solid content of fluids

Ville A. Kaikkonen, Anssi J. Mäkynen, Univ. of Oulu (Finland)

Digital in-line holographic microscopy (DIHM) is a captivating imaging method for industrial applications where large volumes of fluids are to be imaged with microscopic resolution. The lensless holographic in-line imaging setup with a point light source, also known as Gabor setup, can be build up with just few components and the components needed are also fairly low cost. DIHM is by its principle well suited for imaging large volumes with low concentration of scattering particles, as most of the light emitted from the point source should pass through the image volume unscattered. The large depth of field of DIHM makes it possible to image larger volumes with comparable resolutions than what can be achieved with traditional light microscopy methods using low magnification objectives. Despite the many advantages gained over traditional microscopic methods by the use of DIHM for imaging large volumes, so far it has been utilized most widely in biological and particle image velocimetry (PIV) studies. The large depth of field of the DIHM allows simultaneous imaging of particles located at different depths without need for mechanical scanning, and allows the use of large diameter fluidic channels which are not as prone to clogging and also allow higher flow rates than smaller fluidic channels. In this paper, we present a DIHM based measurement principle for acquiring solid particle content of liquids. The method proposed is demonstrated on bio-oil samples whose solid contents are less than 0,01 wt%. The imaging system applied for the tests consisted of a 405 nm laser light source together with a 0,5 micron pinhole and a four megapixel grayscale CMOS-camera with a pixel size of 6 microns. The oil samples with thicknesses of 5 mm were imaged with lateral resolution better than 10 microns within the whole sample volume.

8776-18, Session 4

Web service for digital holographic video processing

Dmitry A. Ekimov, Petrozavodsk State Univ. (Russian Federation); Anssi J. Mäkynen, Univ. of Oulu (Finland)

Digital holography has been utilized in different imaging applications, such as flow dynamics measurements, cell biology, microparticle imaging and tracking, etc. The holograms are recorded using a digital image sensor and reconstructed numerically. The straight access to the complex amplitude information provides a lot of possibilities for image processing, such as filtering, analyzing and extracting the position, size and shape of the objects in the imaged volume. However, the complex amplitude reconstruction and additional analysis require high computing power. The requirements for the computing power are even higher for applications where multiple sensors are needed. These include sensor networks, for example, consisting of tens or hundreds of holographic imagers distributed in a large area such as natural or industrial water systems. Such sensor networks could be used for monitoring the condition of an inland lake or seashore by means of plankton analysis. In such a case local processing of the holographic data is possible, but it leads to complicated and expensive systems and decreases mobility of the sensors.

A web-service for digital video hologram processing based on Berkeley Open Infrastructure for Network Computing (BOINC) is proposed. The web-service reduces the cost of the sensors connected to the system because the holographic video data is processed on the server side. Parallel computing hardware consisting of graphic processing units (GPUs) and BOINC platform have been utilized. The developed cloud computing provides services as complex amplitude reconstruction, automated detection, focusing and size distribution analysis of the objects. Proof-of-concept is demonstrated by presenting snapshots from holographic video of swimming zooplankton. The snapshots were reconstructed using the proposed web-service.

8776-19, Session 5

Self-diffraction holographic techniques for investigation of photosensitive materials

(Invited Paper)

Lucila H. D. Cescato, Luis F. de Avila, Univ. Estadual de Campinas (Brazil); Marcelo Nalin, Univ. Federal de São Carlos (Brazil)

Holographic techniques are powerful tools to study photosensitive materials due to the high sensitivity of diffraction measurement and the ability to detect dynamic gratings. The technique consist in to project an interference fringe pattern into the photosensitive material and to measure the optical changes, induced in the material, using generally an auxiliary laser beam. In the self-diffraction technique we measure directly the diffraction of the interfering beams, at the grating generated in the photosensitive material. Besides the higher sensitivity, such measurement allows to measure simultaneously and separately the phase and the amplitude grating contribution.

Through a detector, placed behind the photosensitive material, and connected simultaneously to two lock-in amplifiers, switched at the frequency (omega) and 2(omega), respectively, we can measure voltage signals (Vomega) and (V2omega) proportional to the square root of the diffraction efficiency of the phase and of the amplitude grating respectively. For small modulations such signals are directly proportional to phase and amplitude modulations respectively.

These harmonic signals (Vomega) and (V2omega) are sensitive also to fringe perturbations during the exposure. Thus, in order to warrant the fringe stability during the exposure we placed a reference grating very close to the glass sample, and a second photo-detector, placed behind this grating, and we measure the detector signal through a third lock in amplifier switched at the reference frequency ?. The dc signal furnished by this third lock in amplifier is used to feed a PZT-supported mirror placed in one of the arms of the interferometer in order to correct the fringe perturbations.

Such technique was applied to study different photosensitive materials. In order to demonstrate its potentiality we measured the kinetic constant of the photo-reaction in positive photoresists (AZ types) and negative SU-8 photoresist, as well as the maximum values of the refractive index and of the absorption coefficient modulations induced in these materials by different wavelengths of exposure. The same measurement of maximum phase and amplitude modulations were performed in chalcogenides glasses in order to evaluate the potential of such materials to be used as optical data storage devices.

8776-20, Session 5

Three-dimensional multiplexing method with spherical reference beam

Hiroyuki Kurata, Shohei Ozawa, Kaito Okubo, Takaaki Matsubara, Shuhei Yoshida, Manabu Yamamoto, Tokyo Univ. of Science (Japan)

First of all, the explanation about our experimental system is shown below.

We used blue laser of which wavelength is 405nm and as a data pattern, a two dimensional binary bits pattern was prepared. The beam from the laser is split by a half mirror. The one goes through a beam expander and is given signal of data pattern by SLM as a signal beam. Another goes through the objective lens as a reference beam. The objective lens of which NA is 0.4 made the reference beam spherical. These two beams interfered with each other in the medium and record a hologram. The medium is disk shaped and 1.5 mm thick. Finally a detector catches the reconstructed signal when only the reference beam emits to read out. That's our experimental system. Next, our approach is shown below. We examined shift selectivity for the track direction, radial direction, and vertical direction to the medium. Based on the result, we attempted to record holograms corresponding to several Tbits per inch square recording density.

Experimental procedure is as follows. First, we recorded a series of holograms by using shift multiplexing and with rotating the medium and measured diffracted power of each hologram. Next, we recorded holograms as a same way with moving the medium along the vertical direction afterwards we measured diffracted power of each hologram. Next, we similarly recorded with moving the medium along the radial direction and measured diffracted power of each hologram. As a result, we obtained shift selectivity of each three direction.

Based on this result, we suggest how to achieve the high density recording using shift multiplexing method.

First, we recorded a series of holograms by using shift multiplexing and with rotating the medium. Next, we moved the medium along the vertical direction to the medium 200µm then recorded different series of holograms with rotating the medium as if this medium has the multi layers. Next the medium moved along the radial direction 300µm and recorded holograms in the same way and if we repeat this procedure, more than 1 Tbites of data is going to be written in a CD size medium.

This result concludes that we found the shift selectivity of each three direction and using those effectively, we verified we can record more than 1 Tbites of data in a CD size medium. Furthermore, to raise NA of the objective lens, shift selectivity of each three direction is getting better than now. Experimental results show our system is efficient for high recording density and has potential of higher density.

8776-21, Session 5

Volume holographic recording in photopolymerizable nanocomposite materials based on radical-mediated thiol-yne step-growth polymerizations

Ken Mitsube, Yuki Nishimura, Shingo Takayama, The Univ. of Electro-Communications (Japan); Kohta Nagaya, The Univ .of Electro-Communications (Japan); Yasuo Tomita, The Univ. of Electro-Communications (Japan)

Photopolymerizable nanoparticle-polymer nanocomoposite (NPC) materials are constructed by uniformly dispersing nanoparticles to a photopolymer host. Nanoparticles can be assembled under holographic exposure, providing high-contrast (multi-dimensional) photonic lattice structures. The inclusion of nanoparticles in photopolymers capable of the chain-growth free radical polymerizations also provides a reduction in polymerization shrinkage and the improvement of thermal stability of recorded volume holograms at the same time. So far, we have experimentally demonstrated these attractive properties in volume holographic recording and their applications to holographic digital data storage, nonlinear optics and neutron optics. Recently, we have shown that the use of radical-mediated thiol-ene step-growth photopolymerizations provides a further reduction in shrinkage.

The main idea of using the step-growth photopolymerizations for volume holographic recording stems from the fact that while high molecular-weight polymer is not obtained until the later stage of the step-growth polymerization process. As a result, gelation takes place late in conversion, leading to a substantive reduction in shrinkage and stress. The thiol-ene polymerizations proceed by a step-growth radical addition mechanism via sequential propagation of a thiyl radical through a vinyl (an ene) functional group and the subsequent chain transfer of a generated vinyl sulfide radical to a thiol, regenerating a thiyl radical and forming a thioether. Thus, the thiol-ene polymerizations proceed very rapidly but will not reach the gel point until high functional group conversions, giving low shrinkage. However, the thiol-ene polymerizations typically result in low crosslinking densities and thereby low glass transition temperatures, showing the limited thermal stability of a recorded hologram. This is so because the conversion of a vinyl to a thioether provides the vinyl group as monofunctional.

In this work we propose the use of a radical-mediated thiol-yne step-growth photopolymerizations for volume holographic recording in NPC films to overcome the above-mentioned drawback but retain the advantage (i.e., low shrinkage) in the thiol-ene photopolymerizations. The thiol-yne photopolymerization mechanism is different from the thiol-ene photopolymeriztions in the sense that each alkyne functional group can react consecutively with two thiol functional groups. A thiyl radical adds across the alkyne “triple bond”, forming a vinyl sulfide radical. This radial abstracts a hydrogen atom from a thiol, regenerating a thiol radical and forming a vinyl sulfide. Then, a thiyl radical adds across the “double bond” of the vinyl sulfide, generating a dithioether radical. Then, this radical abstracts a hydrogen atom from a thiol, regenerating a thiyl radical and forming a dithioether. We show that thiol-yne based NPC films give the saturated refractive index modulation as large as 0.008 and the recording sensitivity as high as 2005 cm/J at a wavelength of 532 nm, larger than the minimum acceptable values of 0.005 and 500 cm/J, respectively, for holographic data storage. We also show that the shrinkage of a recorded hologram can be as low as that of thiol-ene based NPC films and that the thermal stability is improved better. We demonstrate digital data page recording in thiol-yne based NPC films, showing the symbol error rate and the signal-to-noise ratio to be 0.00028 and 8, respectively.

8776-22, Session 5

Analysis of the effects of viscosity, volume, and temperature in photopolymer material for holographic applications

Jinxin Guo, Univ. College Dublin (Ireland); Michael R. Gleeson, National Univ. of Ireland, Maynooth (Ireland); John T. Sheridan, Univ. College Dublin (Ireland)

In recent work carried out, we introduced the developments made to the Non-local Photo-polymerization Driven Diffusion model, and illustrate some of the useful trends, which the model predicts and then analyse their implications on photopolymer improvement. The model was improved in its physicality through the inclusion of viscosity effects (changes in fractional free volume), multiple components and their photo-kinetic and photo-physical behaviour, and free space vacuoles. In this paper, we further explore this model to provide a more rigorous and informed basis for predicting the behaviours of photopolymer materials in both photo-chemical and photo-physical sides. Such improvements include a) the analysis of the effects of viscosity on the refractive index modulation, b) the effects of the introduction of free space holes, e.g. the volumetric changes, and c) an examination of the effects of local temperatures and various concentration ratios to optimise material performance.

8776-23, Session 5

GPU-based calculations in digital holography

Roque Fernando Madrigal, Pablo Acebal González, Salvador Blaya, Luis Carretero López, Antonio Fimia-Gil, Francisco A. Serrano, Univ. Miguel Hernández de Elche (Spain)

One of the main problem in digital holography is the use of high cost computational calculations such as Fourier transform or diffraction integrals. Furthermore, as the size of the hologram raises, the complexity of the calculations exponentially increases. This fact implies that the best performance can not be obtained for real-time digital holography. Moreover, in last years due to the increase on computational capacity, these drawbacks can be overcame, however CCD devices have simultaneously reached higher resolutions, resulting in an amount on the calculations.

Recently, the performance of video graphical cards has significatively increased. This fact is mainly given by the higher number of GPUs (Graphical Processing Units) which can efficiently calculate these graphical tasks. Within this new paradigm, NVIDIA launched a programming environment for graphics cards (GPU), known as CUDA. This environment allows us to program using C/C++, the GPUs and get a high degree of parallelism. In this work we are going to apply these GPUs with CUDA environment for scientific calculations, concretely high cost computations on the field of digital holography.

We have studied three typical problems in digital holography such as Fourier transforms, Fresnel reconstruction of the hologram and the calculation of vectorial diffraction integral. For this, in all cases the runtime at different image size and the corresponding accuracy were compared to the obtained by traditional calculation systems. The Fourier transforms calculations have been realized by the algorithms included in the SDK of Cuda, while the algorithms used by the Fresnel transforms and the diffraction integral were performed by us.

Fourier transform calculations were performed for different image sizes and accuracies, and several types of input. In the case of the application of Fresnel transform for the reconstruction of holograms, it has been analyzed the runtime for different sizes and precisions. Finally, the higher cost calculation performed on this work has been the vectorial diffraction integral. For this, by using shared memory, a reduction scheme and without the use of any kind of additional library, the whole algorithm for parallel run have been optimized.

The programs have been carried out on a computer with a graphics card of last generation, Nvidia GTX 680, which is optimized for integer calculations. As a result a large reduction of runtime has been obtained which allows a significant improvement. Concretely, 15 fold shorter times for Fresnel transform calculations and 500 times for the vectorial diffraction integral. These initial results, open the possibility for applying such kind of calculations in real time digital holography.

8776-24, Session 6

Design and fabrication of two-dimensional hexagonal photonic crystals with a linear waveguide in Erbium-doped GeO2Bi2O3PbOTiO2 glasses

Luis F. de Avila, Univ. Estadual de Campinas (Brazil) and Univ. Federal de São Carlos (Brazil); Juliana M. P. Almeida, Univ. de São Paulo (Brazil); Paula S. Valle, Univ. Federal de São Carlos (Brazil); Marcos S. Gonçalves, Univ. Estadual de Campinas (Brazil); Cleber R. Mendonça, Univ. de São Paulo (Brazil); Marcelo Nalin, Univ. Federal de São Carlos (Brazil); Lucila H. D. Cescato, Univ. Estadual de Campinas (Brazil)

In this work, we designed and recorded a two-dimensional Hexagonal Photonic Crystals (2D-HPC) layer, with a linear waveguide, in erbium doped GeO2Bi2O3PbOTiO2 glass films, by combining the techniques of holographic recording and femtosecond (fs) laser micromachining.

2D-HPC can be recorded holographically by exposing a photoresist film to the same interference pattern twice and rotating the sample of 60° between the exposures. Such process generates high contrast

masks, however, the cross section of the structures are elliptical instead of circles.

In the first step, the positive photoresist SC 1827 film is deposited by spin coating on a glass substrate. After the double exposure, the photoresist film was developed in AZ Developer diluted 1:4 during 40 s in order to obtain the photoresist template. The resulting structures recorded in photoresist were analyzed by scanning electron microscopy SEM. They are constituted of well-defined elliptical cross section columns measuring around 0.6 µm in height and an average filling factor around 0.2.

The recording of the waveguide is made by a fs laser micromachining system focused at sample surface. The laser spot produces the ablation of the photoresist columns generating a line of defects in the periodic hexagonal array. After the recording of the photoresist template the erbium doped GeO2Bi2O3PbOTiO2 film is evaporated on the photoresist and finally the photoresist template is removed using acetone.

The glass sample was prepared by the fusion method, followed by heat shock. Once obtained the glass, it is used as a target in an electron beam deposition system to obtain the glassy films. The films were evaporated in an EB-PVD system with vacuum (5x106 Torr) at room temperature using 5 kV of voltage and current of 10 mA.

The design of the geometrical parameters of the 2D-HPC is performed by calculation of the dispersion mode curves of the photonic crystal using a 2D finite element method. The proper geometrical parameters depend on the refractive index of the glass film and of its thickness. Such parameters and as well as the period of the 2D-HPC are defined in order to obtain a photonic band gap in the region of erbium luminescence band. In such condition the erbium luminescence will propagate only trough the waveguide.

8776-25, Session 6

Investigation of the electromagnetic behavior of AA/PVA based photopolymer material

Haoyu Li, Yue Qi, Jinxin Guo, Univ. College Dublin (Ireland); Michael Gleeson, Department of Computer Science, NUIM, Maynooth (Ireland); John T. Sheridan, Univ. College Dublin (Ireland)

The photopolymer materials in Holographic Data Storage (HDS) have been increasingly studied due to their growing interest in applications. In this article we make use of the time varying parameters to study the behaviors of the photopolymer materials during exposure time. The nonlocal photo-polymerization driven diffusion (NPDD) model and electromagnetic field principles of Maxell equations are combined using in our model development. Moreover in this model, the theories of the material molecule polarization and the excited photosensitizer conductivity production are also introduced. The numerical simulation results in both cases of single and two beams transmittance and the probe beam diffraction efficiency are all analyzed. Several physical parameters and photochemical rate constant values are estimated by fitting the model to the experimental results.

8776-26, Session 6

Preliminary femtosecond irradiation results of chicken lenses analyzed by digital holographic microscopy

Antonio Fimia-Gil, María Gomariz, Angel Murciano, Pablo Acebal González, Roque Fernando Madrigal, Luis Carretero López, Univ. Miguel Hernández de Elche (Spain); Jorge L. Alió, Alejandra Rodríguez, Vissum Oftalmológica Corp. (Spain); Eduardo Fernández, Univ. Miguel Hernández de Elche (Spain)

Recently, the digital holographic microscopy has experienced an important development in the field of biophotonics, since it is a non-invasive optical method which allows tissues to be visualized in three dimensions and measures their size with a resolution that is within the field of nanometre.

Lately, a set of new optical systems based on femtosecond laser has been developed for cataract surgery application. In this communication we present our first experimental results of crystalline lenses irradiated obtained with ultrashort pulse lasers at high repetition rate.

Ex vivo chicken lenses were processed with two solutions (four lenses in BSS and four lenses in Trypan Blue). The irradiation was done with the Ti:Zafire laser which irradiates at 800 nm with a repetition rate of 76 MHz. The average intensity used was 300mW, with pulses of 4 nJ. The temporal pulse width used on the tissue was 170 fs. The optical irradiation system was a 10X objective microscope long working distance with numerical aperture of 0.3. The crystalline lenses were irradiated simultaneously with the computer controlled XY platform. During this irradiation process, we applied different speeds of movement onto tissue (1 and 10 microns/sec).

The holographic images obtained have given us information about the focusing process on the lens capsule as well as its rupture, thus indicating the level of penetration in the lens and capsule rupture. We irradiated both, the anterior and posterior side of the lenses, which allowed us to analyze the influence of the irradiation process and the curvature degree on both sides of the lens.

The results obtained in these first experiments allow us to establish protocols and techniques to break the crystalline lens capsule as well as to carry out internal tissue modifications. Since the optical system works in real time, it is possible to perform dosimetry measurements in the light-crystalline lens interaction processes giving quantitative information about the breakdown of the tissue structures.

In future projects the possible side effects of thermal action and local modification of the capsule will be analyzed; these are important aspects in the field of non-invasive crystalline lens surgery.

8776-27, Session 6

Vertical light-emitting diodes with SiO2 two-dimensional light extractor by holographic lithography

Sang-Mook Kim, Korea Photonics Technology Institute (Korea, Republic of); Hyokun Son, Chonnam National Univ. (Korea, Republic of); Su Chang Ahn, Kwang-Cheol Lee, Nam Hwang, Korea Photonics Technology Institute (Korea, Republic of)

GaN-InGaN vertical-injection light-emitting diodes (V-LEDs) with SiO2 nanorods arrays were demonstrated to enhance the light extraction efficiency and the light propagation to the side. Laser holographic lithography was used to make a periodic dot pattern for the nanorods. After the first exposure, the sample was rotated by 90o and another exposure was then executed for the two dimensional (2-D) features.

The light output power of the V-LEDs with nanorods is enhanced 4 % compared to the conventional V-LEDs. Furthermore, the full-width at half-maximum (FWHM) of the radiation patterns of the V-LED with nanorods (115~117 o) is extract than the conventional V-LEDs (~ 108~110 o). Based on the measured far-field radiation patterns, the nanorods suppress the total internal reflection and extract the light to the side of the thin-GaN LED.

We believe that V-LEDs with nanorods are more suitable for applications in solid state lighting and displays by extracting the radiation profile.

8776-29, Session 6

Holographic characteristics of modified photo-thermo-refractive glass

Sergey Ivanov, National Research Univ. of Information Technologies, Mechanics and Optics (Russian Federation)

A comparison of the spectral and holographic characteristics of holograms, written in the classical and the modified photo-thermo-refractive (PTR) glass. For compare were used holograms with same expose doze and thermal treatment, also were compared holograms with optimal parameters of exposition and thermal treatment for each glass. Classic PTR glass has a large optical loss (> 0.5 cm^-1) in visible spectrum, due to the absorption band of colloidal silver

with ?max = 450 nm. This is considerably restricts the application of hologram in the blue-green spectral region.Was shown that hologram in a modified PTR glass have no additional absorption band of colloidal silver nanoparticles. This allows recording in a modified PTR glass pure phase holograms. Increase in refractive index of holograms in a modified PTR glass is 2 times greater than in the classic PTR glass. Maximum increase of the refractive index (?n = 10.2?10^-4) for the modified glass PTR reached at exposures 7 times lower than that of the classical PTR glass (?n = 4.5?10^-4).

8776-9, Session PS

The optical scheme for recording of miniature light guide holographic indicator

Artem Solomashenko, Sergey B. Odinokov, Vladimir V. Markin, Alexey S. Kuznetsov, Ekaterina Drozdova, Bauman Moscow State Technical Univ. (Russian Federation)

During the last years significant progress in the field of information display is reached. The use of light-guide plates with HOE can substantially reduce the weight and dimensions of the display system.

Holographic display is a glass plate, in which the light is propagated under the total internal reflection (TIR), with HOE recorded on its surface, and a prism to introduce light into the glass plate. Using the prism light is introduced into the plate at an angle of total internal reflection, and is propagated in it. When the light reaches the surface of the plate with a HOE, part of the light emerges from it. As a result the small size of the exit pupil of the projection system is "stretched" by the indicator to the zone much larger sizes due to multiple overlapping individual pupils in area of the operator's eye.

In general, the HOE are two diffraction gratings: the first - to emerge the light, and the second - intermediate - deploys radiation for the expanding the image along one axis. Both of these gratings should have different diffraction efficiency for alignment in the surveillance area the brightness of the observed image. As the recording material is used photoresist. The main advantage of photoresists as opposed to other photosensitive materials for holography is their dimensional stability, absence of selectivity and simple replication technology.

To obtain a diffraction grating the optical scheme was proposed. A distinctive feature of this optical scheme is the zone record of diffraction gratings, i.e., grating is divided into separate fragments that stitching at the recording process with a high-precision motion system of the plate with the photosensitive layer. Record of separate zones allows you to simply get HOE and diffraction gratings, respectively, and holographic indicators of large size. There is no need to significantly expand the beam, providing uniform illumination of the plate, which is a significant advantage of such a scheme.

In this scheme to record the diffraction grating with variable diffraction efficiency does not use transparencies with nonlinear transmission or moving masks, and different diffraction efficiency is provided by changing the exposure for each zone, on which the grating is divided. Thus, due the specially developed for this purpose the software, you can record the required distribution of exposure doses calculated for each zone. You can also set the nonlinear change of exposure value for each zone, and quickly adjust the exposure of grating fragments setting the desired value manually. In addition, the recording of separate grating fragment does not exceed a few tens of seconds, thus avoiding the effect of vibrations and other external factors.

Due to the developed optical recording system holographic display with a 120 x 80 mm was obtained and the zone size was 5 x 5 mm.

8776-12, Session PS

The 'hidden image' effect in security holograms and its personalization by laser demetallization.

Andrejs Bulanovs, Edmunds Tamanis, Vadims Kolbjonoks, Daugavpils Univ. (Latvia)

The given work investigates principles of recording, calculation and security aspects of 'hidden image' effect in digital holograms that intended for security applications. Dot-matrix and image-matrix technologies of optical recording can be widely used for producing protective holograms with such type of security features. When a collimated laser beam is fall on and then is reflected from section of the holograms containing a 'hidden image' protective element, a graphic image can be seen in the projection of diffracted light on the frosted screen. The present work also discusses a method of personalizing the 'hidden image' effect with the help of laser demetallization. The hidden image in this way can be individualized for each individual hologram sticker and contain additional information such as a number, text or logotype. The attractiveness of this method is in the possibility of a considerable increase of the protective characteristic of holograms and incorporation of additional variable information in it, as well as in provision of both visual and automatic ways of checking authenticity of a hologram.

8776-28, Session PS

Holographic memory based on computer generated Fourier-holograms

Sergey B. Odinokov, Bauman Moscow State Technical Univ. (Russian Federation); Evgeny Y. Zlokazov, Rostislav S. Starikov, Nikolay N. Evtikhiev, National Research Nuclear Univ. MEPhI (Russian Federation); Vladimir Bobrinev, Nina M. Verenikina, Bauman Moscow State Technical Univ. (Russian Federation); Sergey N. Starikov, National Research Nuclear Univ. MEPhI (Russian Federation); Aleksander Betin, Alexander Y. Zherdev, Dmitriy S. Lushnikov, Vladimir V. Markin, Bauman Moscow State Technical Univ. (Russian Federation)

Classic holographic memory systems use two-beam approach based on fixation of interference pattern between object and reference coherent beams on holographic recording medium. The size of single pattern is about several micrometers. High precision optical set up is required to form such a microhologram, which is the reason of excessive price for holographic data recording devices. Methods of computer holographic synthesis allow to calculate holographic patterns numerically as 2D images. These images can be realized with the use of spatial light modulator, then reduced in optical projection system and exposed on holographic medium. In this paper we represent the research of holographic memory system based on computer generated Fourier holograms projection.

Conference 8777A: Damage to VUV, EUV, and X-ray Optics IV

Monday - Tuesday 15–16 April 2013

Part of Proceedings of SPIE Vol. 8777 Damage to VUV, EUV, and X-ray Optics IV; and EUV and X-ray Optics: Synergy between Laboratory and Space III

8777-1, Session 1

Development, experimental performance and damage properties of x-ray optics for the LCLS free electron laser *(Invited Paper)*

Regina Soufli, Mónica Fernández-Perea, Lawrence Livermore National Lab. (United States); Jacek Krzywinski, David W. Rich, SLAC National Accelerator Lab. (United States); Sherry L. Baker, Jeffrey C. Robinson, Stefan P. Hau-Riege, Lawrence Livermore National Lab. (United States); Eric M. Gullikson, Valeriy V. Yashchuk, Wayne R. McKinney, Lawrence Berkeley National Lab. (United States); Philip A. Heimann, William F. Schlotter, Michael Rowen, Paul A. Montanez, Sebastien Boutet, SLAC National Accelerator Lab. (United States)

The Linac Coherent Light Source (LCLS) x-ray free electron laser (FEL) has been operational since 2009 at the SLAC National Accelerator Laboratory in California. This first-of-a-kind x-ray source produces ~100 femtosecond monochromatic x-ray pulses of unprecedented brightness (about 10 orders of magnitude higher than current 3rd generation synchrotron sources) in the soft and hard x-ray energy range. The revolutionary capabilities of the LCLS are generating a wealth of new research in the fields of physics, biology and materials science. The extremely high instantaneous dose of the LCLS beam led to x-ray optics consisting of an especially modified reflective coating (boron carbide for the soft x-ray optics and silicon carbide for the hard x-ray optics) deposited on a silicon substrate. Furthermore, wavefront coherence preservation requirements led to very stringent surface figure and finish specifications for the LCLS optics. This talk will present highlights from the development and experimental performance of x-ray mirrors and gratings for the Soft X-ray materials science (SXR) and Coherent X-ray Imaging (CXI) LCLS instruments. The talk will also discuss results from the first exposures of boron carbide reflective coatings at photon energies near the Carbon K edge at LCLS.

8777-2, Session 1

Investigation on the state of a DLC-coated plane mirror after two years of use at the FLASH-VUV-FEL at DESY

Frank Siewert, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Frank Scholze, Physikalisch-Technische Bundesanstalt (Germany); Michael Störmer, Helmholtz-Zentrum Geesthacht (Germany); Kai Tiedtke, Deutsches Elektronen-Synchrotron (Germany)

Ultra-precise X-ray mirrors are used under grazing incidence condition for beam steering, beam alignment and monochromatisation at fourth generation light sources like Free-Electron Lasers as FLASH or the European XFEL. Such optics are exposed to high energy photon beams and have to withstand extreme high peak power generated by the FEL-source. However, any degradation on the mirror shape - even in nanometer-scale - will cause significant impact on the coherence and wave-front properties of the synchrotron beam. We will show investigations on the mirror state after two years use in the beamline 3 at DESY's FLASH-VUV Free Electron Laser in Hamburg. We inspect a plane mirror of 510mm in length, coated with amorphous carbon (DLC) of 45 nm thickness. To investigate the state of the mirror shape, we applied techniques of ex-situ metrology like slope measuring profiler, white-light-interferometry (WLI) and an atomic force microscope (AFM). In addition, we performed at wavelength-metrology at the EUV-reflectometry facility of the PTB at the BESSY-II storage ring in Berlin. The slope and micro-roughness measurements showed no significant change of the mirror figure profile. A slight increase of the micro-roughness is found for higher spatial frequencies. Measurements of the reflectance showed a slight decrease mainly in the mirror centre region. We will show and discuss the achieved results in detail.

8777-3, Session 2

VUV-UV multiwavelength excitation process for high-quality ablation of fused silica *(Invited Paper)*

Koji Sugioka, Katsumi Midorikawa, RIKEN (Japan)

Development of precision microfabrication techniques for hard materials such as fused silica and GaN is strongly desired in various industrial fields. Although pulsed laser ablation is quite attractive for high-quality and high-efficiency microfabrication of various kinds of materials, conventional UV, visible or IR lasers often induce severe damage and cracks in the hard materials due to their weak absorbance and/or small photon energy. To overcome this problem, VUV-UV multiwavelength excitation process has been originally developed, in which vacuum ultraviolet (VUV) laser beam and the ultraviolet (UV) laser beam are simultaneously directed to substrates for high-quality ablation of the hard materials. In this process, the energy density of the VUV laser is as small as several tens - a few hundreds mJ/cm2, while that of the simultaneously irradiated UV laser beam is of the order of 1 J/cm2. The multiwavelength excitation process achieves high quality ablation of the hard materials almost similarly to conventional single-VUV laser ablation. Moreover, the former process has some advantages over the latter process. Namely, 1) the small fluence of the VUV laser in the former processing reduces the photon cost of the high-fluence VUV laser in the latter processing. 2) Therefore, the processing area and throughput increase. 3) Besides, since ablation proceeds via the UV laser beam, the necessity for expensive VUV optics and projection system is eliminated. In our study, F2 (157 nm) was used as a light source of VUV and KrF excimer (248 nm) as UV. In the experiments, they are collinearly introduced to the substrates. In order to investigate the role of the VUV beams, we measured the absorption by fused silica of KrF excimer laser beam induced by simultaneous irradiation with the F2 laser beam, which revealed that simultaneous irradiation by the F2 laser induced a large absorption by the fused silica of the KrF excimer laser beam. This phenomenon can be explained as excited state absorption (ESA) induced by coupling the KrF excimer and F2 laser beams. Namely, electrons are first excited from valence band to the excited state (defect level) by F2 laser beam and then the excited electrons further absorb the KrF laser beam to be excited beyond the vacuum level, leading to Si-O bonds and finally causing effective ablation. To optimize and strengthen the mechanism discussed above, the ablated samples prepared with various conditions were characterized.

8777-4, Session 2

Characterisation of EUV damage thresholds and imaging performance of Mo/Si multilayer mirrors

Matthias Müller, Laser-Lab. Göttingen e.V. (Germany); Frank Barkusky, KLA-Tencor Corp. (United States); Torsten Feigl, Fraunhofer-Insitut für Angewandte Optik und Feinmechanik IOF (Germany); Klaus Mann, Laser-Lab. Göttingen e.V. (Germany); Torsten Feigl, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany)

Currently, more and more powerful EUV sources for next generation semiconductor microlithography are being developed, for which novel optical elements like multilayer or grazing-incidence mirrors are required. Consisting of very thin alternating layers, especially molybdenum and silicon for the wavelength of 13.5 nm, multilayer mirrors are typically employed for near-normal reflection angles. These mirrors are presently being optimized with respect to thermal resistivity

and reflectivity. However, only very few ablation and damage threshold studies at a wavelength of 13.5 nm are available up to now for these optical elements.

We studied 1-on-1 and 10-on-1 damage thresholds of Mo/Si multilayers with EUV radiation of 13.5 nm wavelength, using a table-top laser produced plasma source based on solid gold as target material. The experiments were performed on different types of Mo/Si mirror, showing no significant difference in single pulse damage thresholds. However, the damage threshold for ten pulses is ≈60 % lower than the single pulse threshold, implying a defect dominated damage process. Using Nomarski (DIC) and atomic force microscopy (AFM) we analysed the damage morphologies, indicating a primarily thermally induced damage mechanism for higher fluences.

Additionally, we characterised transmission and reflection properties of novel Mo/Si multilayer beam splitters performing wavefront measurements with a Hartmann sensor at 13.5 nm wavelength. Such wavefront measurements allow also actinic investigations of thermal lens effects on EUV optics.

8777-5, Session 2

Responses of organic and inorganic materials to intense EUV radiation from laser-produced plasmas *(Invited Paper)*

Tetsuya Makimura, Shuichi Torii, Univ. of Tsukuba (Japan); Daisuke Nakamura, Akihiko Takahashi, Kyushu Univ. (Japan); Hiroyuki Niino, National Institute of Advanced Industrial Science and Technology (Japan); Kouichi Murakami, Univ. of Tsukuba (Japan)

We have investigated responses of polymers to EUV radiation from laser-produced plasmas beyond ablation thresholds and micromachining. We concentrated on fabricate precise 3D micro-structures of PDMS, PMMA, acrylic block copolymers (BCP), and silica. The micromachining technique can be applied to three-dimensional micro-fluidic and bio-medical devices. The EUV ablation is promising to realize a practical micromachining technique. In the present work, we used two EUV radiation sources; (a) Wide band EUV light in a range of 10-300 eV was generated by irradiation of Ta targets with Nd:YAG laser light at 500 mJ/pulse. (b) Narrow band EUV light at 11 and 13 nm was generated by irradiation of solid Xe and Sn targets, respectively, with pulsed TEA CO2 laser light. The generated EUV light was condensed onto the materials at high power density beyond the ablation thresholds, using ellipsoidal mirrors. We found that through-holes with a diameter of one micrometer can be fabricated in PMMA and PDMS sheets with thicknesses of 4-10 micrometers, at 250 nm/shot. The effective ablation of PMMA sheets can be applied to a LIGA-like process for fabricating micro-structures of metals for micro- and nano-molds. Further, high quality nano- and microstructures can be fabricated on silica glass surface. Typically, we have achieved 1 nm roughness after EUV ablation by 500 nm in depth. The more precise structures can be fabricated on all of the investigated materials than those fabricated by conventional visible and ultraviolet lasers. The most crucial factors for the ablation process are most possibly short-wavelengths and high power density. In the case of silica, ablation is suggested to be governed by Column repulsion of EUV-generated ions.

8777-6, Session 2

Application of EUV optics to surface modification of materials

Oleksandr Frolov, Karel Kolacek, Jiri Schmidt, Jaroslav Straus, Vaclav Prukner, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic); Andrei Choukourov, Charles Univ. in Prague (Czech Republic)

Many applications require surface modification and micro-structuring of polymers. For these purposes is mainly used ultraviolet radiation from excimer lamps or excimer lasers. However, these sources have a decided disadvantage - degrading the polymer deep inside due to relatively big radiation penetration depth which may exceed 100 ?m.

Ablation of organic polymers by extreme ultraviolet (EUV) radiation with wavelength shorter than 100 nm is discussed in a relatively small number of publications. It was shown that soft X-ray or EUV radiation can be utilized for direct photo-etching and surface modification of materials due to very short absorption length of EUV photons in any material (approximately 100 nm only). Photo-etching of inorganic materials is also possible but requires higher EUV fluence in relation to polymers. Early poly(butene-1-sulfone), polymethylmethacrylate (PMMA), polyethylene terephthalate and polytetrafluoroethylene (PTFE) were ablated by incoherent, nonmonochromatic EUV emission from laser-produced plasma. A Z-pinch plasma was used as an EUV source for ablation of PMMA and PTFE. The ablation of polymers was also obtained using EUV radiation from a free-electron laser and EUV synchrotron radiation.

We report results of experiments connected with surface modification of organic and inorganic materials with an intense EUV laser beam. The samples were irradiated by laser beam from a discharge-plasma EUV source (with wavelength 46.9 nm) based on a high-current capillary discharge driver. A detailed description of our driver CAPEX can be found in the early published paper. The laser beam is focused with a spherical (R=2100 mm) Si/Sc multilayer-coated mirror on PMMA, gold-covered-PMMA and gallium arsenide (GaAs) samples. For analysis of laser beam footprints an atomic-force microscope (AFM) was used. It turned out that the energy of focused EUV laser beam is sufficient for ablation not only easily ablative material PMMA but also thin layer of gold (thickness ~40 nm) and GaAs by single shot, even if the focus is significantly influenced by astigmatism (astigmatic difference ~16 mm). Non-thermal desorption/ablation regimes were observed in all materials. Surface of PMMA and GaAs samples was irradiated by single shot and five shots through a small Au grid (step 12.5 x 12.5 ?m, windows 7.5 x 7.5 ?m) closely attached to this surface. Analysis of the exposed regions by AFM show that diffraction pattern in single window of grid in desorption region of footprints on GaAs sample was observed similarly as in earlier experiments with PMMA. On the other hand, in ablation region of footprints, where crater was several time dipper than in desorption region, no diffraction pattern is observed.

8777-7, Session 2

EUV induced ablation and surface modification of poly(vinylidene fluoride) irradiated in vacuum or gaseous environment

Andrzej S Bartnik, Military University of Technology (Poland); Wojciech Lisowski, Janusz Sobczak, Institute of Physical Chemistry Polish Academy of Sciences (Poland); Przemyslaw Wachulak, Boguslaw Budner, Barbara Korczyc, Henryk Fiedorowicz, Jerzy Kostecki, Military University of Technology (Poland)

Extreme ultraviolet (EUV) is strongly absorbed in any material. In polymers the absorption depth ranges from tens to hundreds nanometers depending on the radiation wavelength and chemical composition. A single EUV photon carries enough energy to break several molecular bonds. Long time irradiation of polymers with the fluence far below the ablation threshold leads to the material degradation in a near surface layer. Irradiation with sufficiently high EUV fluence results in the material ablation. For the fluence close to the ablation threshold different kinds of surface modification can occur. The modification concerns both physical and chemical structures.

In this work a laser-plasma EUV source based on a gas puff target was used for ablation and surface modification of poly(vinylidene fluoride) (PVDF). The radiation was focused using a gold-plated grazing incidence ellipsoidal collector. The collector allowed for effective focusing of plasma radiation within the wavelength range 9 – 70 nm. Plasma was produced in a mixture of Kr + 10% Xe giving the most intense emission in relatively narrow wavelength range centred at 11±1 nm. The spectral intensity in the wavelength range beyond 11 nm was much weaker but the spectrally integrated intensities in both ranges were comparable. The EUV fluence in a focal plane of the collector exceeded 60 mJ/cm2 at the centre of the focal spot. The polymer samples were irradiated in the focal plane or at some distance downstream the focal plane of the EUV collector. Additionally different gases could be injected into the interaction region. The injected gas

was ionized and excited by the EUV radiation from a laser-plasma source. The ionization degree and excited states were investigated using an EUV spectrometry and the corresponding spectra are presented. QMS measurements of the ablation products allowed for investigation of decomposition process. The surface morphology after irradiation was investigated using a scanning electron microscope (SEM). The chemical changes in the near-surface layers were investigated by X-ray photoelectron spectroscopy (XPS).

Possibility of efficient micromachining of PVDF by EUV irradiation with the fluence close to the maximum was demonstrated. Mass spectroscopy, employed to investigate the ablation products, revealed emission of numerous molecular species of C-containing fragments of the polymer chain. It was shown that chemical structure of the polymer surface after ablation remains unaltered. On the other hand irradiation of PVDF with low fluence led to chemical changes in a near-surface layer. Chemical modification of the polymer was also obtained after combined EUV and ionized nitrogen treatment. X-ray photoelectron spectroscopy revealed incorporation of nitrogen atoms into the chemical structure of PVDF.

8777-8, Session 3

Non-thermal phase transitions in semiconductors under femtosecond XUV irradiation *(Invited Paper)*

Nikita A. Medvedev, Ctr. for Free-Electron Laser Science (Germany); Harald O. Jeschke, Johann Wolfgang Goethe-Univ. Frankfurt am Main (Germany); Beata Zaija, Ctr. for Free-Electron Laser Science (Germany)

After high energy deposition into a semiconductor or a dielectric, the material properties undergo transient changes, which might lead to an observable permanent material damage. It has been known for over a decade that the intense visible light irradiation of semiconductors induces ultrafast non-equilibrium phase transitions, most famous manifestation of which is non-thermal melting [1]. A solid-solid phase transitions are also known, as, for example, a transition of diamond to graphite. Such an ultrafast transition (within ~100?fs) is driven by the changes in the interatomic potential. This process of ultrafast phase transition (of a timescale comparable with an atomic oscillation scale) takes place before the electron-phonon coupling heats up the lattice.

We investigate wheather the non-thermal melting is a general mechanism of the semiconductor damage under high energy deposition into electronic subsystem of a target, or if it is specific only to a visible light irradiation. We apply a new hybrid model for tracing the laser induced lattice deformations during the femtosecond XUV pulse, taking into account non-equilibrium electron kinetics. The atomic motion is traced with molecular dynamics tool, using the time-dependent potential energy surfaces derived from a microscopic electronic Hamiltonian within the Tight Binding approach [1]. Thermalization effects of electron kinetics, secondary cascades and relaxations are treated by Monte Carlo model for high energy electrons [2,3], with the separate temperature model for the partially thermalized fraction of electrons [4]. The specific shape of the transient electron distribution function, the “bump on hot tail [5]”-distribution, found to be a typical electron distribution on femtosecond timescale under VUV-XUV irradiation [5-6], allowed us to establish a computationally efficient treatment of electron kinetics [7].

We found that the electron relaxation kinetics in diamond took place within 50 fs - 100 fs after the exposure with the short laser pulse (Gaussian, FWHM of 10 fs) at 92 eV photon energy. During this time, the lattice temperature did not increase significantly but the phase transition from a diamond to graphite nevertheless occurred. It was stimulated by a collapse of the band gap, when the number of electron excited into the conduction band overcame the value of 1.5 % of the valence band electrons (corresponds to the 0.7 eV/atom fo deposited dose) [7]. These results demonstrate for the first time the non-thermal melting mechanism of semiconductors under the femtosecond VUV-XUV irradiation, proving the generality of this radiation-induced phase transition [7].

References:

[1] H.O. Jeschke, M.E. Garcia, K.H. Bennemann, Phys. Rev. B 60, R3701 (1999)

[2] N. Medvedev , B. Rethfeld, New J. Phys. 12, 073037 (2010)

[3] N. Medvedev, U. Zastrau, E. Förster, D.O. Gericke, B. Rethfeld, Phys. Rev. Lett. 107, 165003 (2011)

[4] O. Osmani, N. Medvedev, M. Schleberger, B. Rethfeld, Phys. Rev. B 84, 214105 (2011)

[5] D. Chapman, D. Gericke, Phys. Rev. Lett. 107, 165004 (2011)

[6] B. Ziaja, N. Medvedev, HEDP 8, 18 (2012)

[7] N. Medvedev, H.O. Jeschke, B. Ziaja, New J. Phys. 14 (2012)

8777-9, Session 3

Hydrodynamics and detailed atomic physics treatment of XFEL interaction with matter

Olivier Peyrusse, Univ. Bordeaux 1 (France)

References:

O. Peyrusse, Phys. Rev. E, vol 86, 046403 (2012)

O. Peyrusse, J. Phys. B, vol 32, 683 (1999)

J. Gaudin et al, Phys. Rev. B, vol 86, 024103 (2012)

8777-10, Session 3

Numerical study of single shot damage thresholds of multilayer optics for high-intensity short-wavelength radiation sources

Rolf A. Loch, FOM Institute DIFFER (Netherlands); Ryszard Sobierajski, Institute of Physics (Poland); Eric Louis, FOM Institute DIFFER (Netherlands) and Univ. Twente (Netherlands); Jeroen Bosgra, FOM Institute DIFFER (Netherlands); Fred Bijkerk, FOM Institute DIFFER (Netherlands) and Univ. Twente (Netherlands)

The success of high-intensity short-wavelength radiation sources depends to a large extent on the availability of optics that can withstand high powers. Damage studies on optics are therefore of high importance for a proper design of optics in beamlines and end-stations at current and future radiation sources. Experimental studies on damage by high-intensity sources, however, are scarce due to the limited access to such sources. For that reason, we performed a theoretical investigation on many material combinations for multilayer optics for XUV and SXR radiation.

Single shot damage thresholds were calculated for several commonly used multilayer systems and newly proposed material combinations. We used a model that was developed to investigate the damage mechanisms in Mo/Si and MoN/SiN multilayers and applied this model to multilayers suitable for wavelengths down to 2 nm. The described study on the multilayer damage thresholds presents the first investigation of this kind.

We considered multilayers usable below various absorption edges and in the water window and propose several new multilayer systems. For the boron edge the most promising multilayer with high damage threshold is Mo2B5/B4C. Also LaN/B4C has a high damage threshold prospect. For the carbon edge, CoO/C appears to be a good alternative for Co/C and V/C. Also LaN/C shows promise. For the scandium (and vanadium) absorption edge we propose to use V/Sc instead of the commonly used Cr/Sc. The multilayer that shows the highest potential is NiO/Li2O, with a calculated damage threshold of more than 500 mJ/cm2 near the oxygen absorption edge. This multilayer system is a promising candidate for applications in the water window regime.

Our investigation demonstrates that the damage threshold of multilayers can vary over a large range from several tens to several hundreds of mJ/cm2, and that multilayer mirrors are hence a serious candidate as damage resistant optics.

8777-11, Session 3

Global sensitivity analysis of the XUV-ABLATOR code

Vaclav Nevrly, Michal Vasinek, Jaroslav Janku, Jakub Dlabka, VSB-TU Ostrava (Czech Republic); Libor Juha, Ludek Vysín, Tomas Burian, Jan Lancok, Jan Skrinsky, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Zdenek Zelinger, Institute of Physical Chemistry (Czech Republic); Peter Pira, Jan Wild, Charles Univ. in Prague (Czech Republic)

Numerical simulations employing one-dimensional thermomechanic and hydrodynamic models can be efficiently used for predicting the potential damage of optical materials by soft X-ray and extreme ultraviolet (XUV) radiation. These models are also of use for estimating the applicability of different sources of coherent XUV radiation for pulsed laser deposition (PLD) and determining their output parameters. Ablation processes induced by two XUV lasers are considered to be subject of the computer simulation here. The experimental results were obtained with (i) the desktop size capillary-discharge laser (CDL) operating at the fixed wavelength of 46.9 nm corresponding to the radiation transition in neon-like argon ions and (ii) SCSS facility representing compact tunable self-amplified spontaneous-emission free-electron laser (SASE-FEL). The XUV pulses provided by CDL can be characterized by a maximum energy of several ?J and a duration of about 1.5 ns. The SCSS device can reach a pulse energy of several ?J and a pulse duration of 100 fs at the chosen wavelength in the 45-60 nm range. So, it makes possible to study pulse duration effects in the XUV ablation. This work reports the case study performed employing the one-dimensional Lagrangian finite difference thermomechanic model for XUV radiation-induced ablation based on the computer code originally developed by A. T. Anderson for modelling the X-ray ablation occurring potentially in ICF reactors. Modification of the original code was carried out taking into account relatively short attenuation lengths as well as the radiation-induced chemical decomposition occurring in ablated materials. The modified version called XUV-ABLATOR was reported elsewhere. Reasonable agreement between the experimental data and the results of simulations employing XUV-ABLATOR code was also discussed in the frame of previous studies concerning the relationship of ablation rate and laser fluence, e.g. for the first XUV SASE-FEL beam characteristics (30-150 fs pulses at 86 nm; TTF1 FEL operated in Hamburg in 2001). Performance of the XUV-ABLATOR code in predicting this relationship is investigated here in more details for Si (silicon), monocrystaline SiO_2 (quartz), and polymethylmethacrylate (PMMA) as reference materials. Implementation of the original Fortran code (interfaced via the Python script) and the graphical user's interface of XUV-ABLATOR, which was currently developed, is briefly described in this contribution. Global sensitivity analysis was applied in order to identify the most critical input parameters as well as to explore the uncertainty range of modelling results. The high dimensional model representation (HDMR) is an efficient method for constructing a fully functional metamodel and to calculate variance based sensitivity indices. Quasi-random sampling method (Sobol' sequence) was used in order to uniformly cover the input space by selected values of individual variables. The results of HDMR analysis enables to better understand to experimental data and their interpretation by taking into account the uncertainty and sensitivity. Moreover, such approach supports the reliability of specific input data, which are currently collected for UV-Vis-NIR transparent materials (e.g. LiF, CaF_2, MgF_2) targeted by our XUV PLD projects.

8777-12, Session 3

Mechanisms of structural changes induced by electronic excitations in solids *(Invited Paper)*

Yuzo Shinozuka, Wakayama Univ. (Japan)

An overview is presented on various structural changes of non-metallic materials induced by electronic excitations from the viewpoint of energy transfer, relaxation and symmetry breaking. Photonic irradiation to solids excites valence and/or core electrons. The difference of electronic-charge distribution compared to that in the ground state creates the imbalance in interatomic forces. This is the origin of the electron-lattice interaction.

Since valence electron excitations in perfect crystals are all extended Bloch states, their localization process is necessary to induce a local structural change. This is realized by

a) lack of translational symmetry such as impurity, vacancy, dislocation, surface, …

b) self-localization of an electron (hole, exciton) as a result of the strong electron-lattice interaction.

In three- and two-dimensional systems, self-localization only occurs when the electron-lattice coupling exceeds a critical strength. In one-dimensional systems all the electronic excitations are predicted to be always self-localized (self-trapping) without potential barrier. Self-localization of two electrons may occur for high density excitation (bi-polaron effect).

After electron (hole, exciton) localization, further symmetry breaking processes are possible. The (pseudo) Jahn-Teller effect creates the off-center instability of a self-trapped exciton in alkalihalides and a substitutional impurity in covalent semiconductors, such as EL2 and DX-centers. These off-center structures are precursors of defect creation. The phonon-kick mechanism for defect reactions in active semiconductor laser diodes is also discussed in terms of high density excitations.

When the photon quantum energy is so high (as in case of VUV, EUV, X-ray) to excite the core electrons of the constituent atoms, a core hole is created, possibly localized. After a very short life time (< 10-15sec) the core hole is annihilated by the Auger process. There are two type of Auger recombination. One is the participate Auger where the excited electron from the core state excites a valence electron and again recombines with the core hole, leaving one valence hole. The other is the spectator Auger where another valence electron recombines with the core hole leaving two valence holes and one conduction electron. The latter is an effective trigger for defect reactions, because the resulting two valence holes are very effective to interact with the lattice (bipolaron mechanism) in addition to the leaving conduction electron which helps to weaken the bond around it.

In order to understand the underlying mechanism of excitation-induced structural changes, it is important to relate with the initial excitation-condition, the relaxation dynamics and the induced final atomic structure. A brief review will be given on the recent developments of the time dependent observations of the transient structures, such as high time-resolution x-ray and electron diffraction/crystallography, spectroscopy and imaging.

Reference

Y. Shinozuka: Jpn. J. Appl. Phys. 32 (1993) 4560.

Y. Shinozuka: in Materials and Reliability Handbook for Semiconductor Optical and Electron Devices, Ed. by O. Ueda and S. Pearton (Springer-Verlag, Berlin, 2012) Chapt.10.

8777-13, Session 3

Theoretical investigation of scattering properties of crystal exposed to the XFEL femtosecond pulse

Aleksandr V. Leonov, Belarusian State Univ. (Belarus); Dmitriy Ksenzov, Univ. Siegen (Germany); Andrei Benediktovitch, Ilya D. Feranchuk, Belarusian State Univ. (Belarus); Ullrich Pietsch, Univ. Siegen (Germany)

The ultra-bright femtosecond radiation of the X-ray Free Electron Laser (XFEL) provides unique possibilities to study matter with angstrom resolution at timescales corresponding to atomic electron motion. One of the most important parts of the XFEL facilities are the elements of X-ray optics based on diffraction and reflection of the X-ray beams in crystals that allow one to control the path of the X-ray beam and perform the analysis of the results. However, due to the interaction with high-intensity pulse the irradiated object alternates drastically up to its complete destruction. Therefore interaction of the XFEL femtosecond pulses with a crystal is not well understood yet and cannot be described by means of the conventional linear response theory.

In order to analyze the time dependence of the X-ray scattering properties of optical element illuminated by the XFEL pulse we analyze the electron density evolution on the basis of rate equations [1].

Specific features of the problem lead to the inclusion of several new channels in the system of rate equations such as electron-electron collisions, electron impact ionization and three body recombination. In order to consider these channels effectively expressions for the cross sections of these processes are calculated within the framework of the effective charge approximation for the electron configurations in ions [2]. In addition, we consider the Boltzmann equation within the system of rate equations in order to take into account the kinetics of the free electron gas in the medium.

The numerical algorithm and software are developed for calculation of the intensity of the diffraction reflection of the XFEL pulse taking into account the specific characteristics of the kinetic processes in crystal. Numerical results are analyzed on the example of the Si crystal in the wide range of the pulse parameters variation.

References

1. Song-Kil Son, Linda Young and Robin Santra, Phys. Rev. A. 83 (2011), 033402.

2. V. V. Triguk, I. D. Feranchuk, J. Appl. Spectroscopy. 77 (2011), 749.

8777-14, Session 4

Multiple free electron laser pulse illumination of a carbon coated silicon substrate

Björn Siemer, Tim Hoger, Marco Rutkowski, Westfälische Wilhelms-Univ. Münster (Germany); Stefan Düsterer, Deutsches Elektronen-Synchrotron (Germany); Helmut Zacharias, Westfälische Wilhelms-Univ. Münster (Germany)

The fourth generation of XUV-, soft x-ray- and x-ray-light sources, to name the free electron lasers FLASH, LCLS, SACLA, FERMI@Elettra and the European X-FEL, leads to new seminal scientific findings and technical challenges. For the facilities the question of the beam transport is of utmost importance. To provide a good reflectivity over a large range of photon energies up to about 300 eV carbon coated silica mirrors illuminated under gracing incidence angle are mostly chosen. Thereby the coating for the mirrors must tolerate high light intensities at high photon energies and also high repetition rates. In previous experiments single shot exposure damage thresholds were determined to a fluence of 1.1 J/cm^2 at 32.5 nm [1]. Investigations of the multiple-shot exposure below the damage threshold at fluences of 0.5 J/cm^2 at 47 nm shows also a damage of the coatings [2]. No results for the exposure with low fluences but high repetition rates seem to have been reported.

In the present experiment an amorphous diamond-like carbon coated silica substrate was illuminated at photon energies of 21 nm (58 eV) and an average pulse intensity of ~27 µJ/pulse. The ellipsoidal spot size was 300 µm x 600 µm not centered in the 100 µm x 100 µm focus at BL1 at FLASH which leads to a fluence of 0.005 J/cm^2. The influence of multiple (100-20,000) light pulses to the coated surface is analyzed. Therefor different spots on the surface were illuminated with different numbers of FLASH pulses. A change in reflectivity is visible under a light microscope dependent on the number of pulses. An AFM profile and measurements with a profilometer yield no topological changes. The investigation of the illuminated spots with a microfocus Raman spectrometer shows a decrease of the carbon signal at higher pulse repetition rates.

[1] S. P. Hau-Riege, R. A. London, R. M. Bionta, M. A. McKernan, S. L. Baker, J. Krzywinski, R. Sobierajski, R. Nietubyc, J. B. Pelka, M. Jurek, L. Juha, J. Chalupsky, J. Cihelka, V. Hájková, A. Velyhan, J. Krása, J. Kuba, H. Wabnitz, K. Tiedtke, S. Toleikis, T. Tschentscher, M. Bergh, C. Caleman, K. Sokolowski-Tinten, N. Stojanic, and U. Zastrau, Appl. Phys. Lett. 90, 173128 (2007)

[2] L. Juha, V. Hájková, J. Chalupsky, V. Vorlí?ek, A. Ritucci, A. Reale, P. Zuppella and M. Störmer, J. Appl. Phys. 105, 093117 (2009)

8777-15, Session 4

Multiple pulse damage in Mo/Si multilayer optics irradiated by intense short-wavelength FELs

Ryszard Sobierajski, Institute of Physics (Poland); Rolf A. Loch, FOM Institute DIFFER (Netherlands); Eric Louis, FOM Institute DIFFER (Netherlands) and Univ. Twente (Netherlands); Dorota Klinger, Piotr Dluzewski, Institute of Physics (Poland); Marcin Klepka, FOM Institute DIFFER (Netherlands); Fred Bijkerk, FOM Institute DIFFER (Netherlands) and Univ. Twente (Netherlands); Tomas Burian, Jaromír Chalupsky, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Shafagh Dastjani Farahani, European XFEL GmbH (Germany); Vera Hájková, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Marion Harmand, Deutsches Elektronen-Synchrotron (Germany); Jacek Krzywinski, SLAC National Accelerator Lab. (United States); Libor Juha, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Stefan P. Moeller, SLAC National Accelerator Lab. (United States); Jérôme Gaudin, European XFEL GmbH (Germany); Andrzej Wawro, Institute of Physics (Poland)

Multilayer coated optics are used for control of XUV (eXtreme-UltraViolet) and soft X-ray radiation in many fields of science and technology, and the development has experienced a considerable boost by the application in advanced photolithography. A new field is the application in experiments at short wavelength Free Electron Lasers. This includes FLASH (Free electron LASer in Hamburg, Germany) and LCLS (Linear Collider Light Source in Stanford, USA) sources, operating in two spectral regimes: XUV and soft X-ray, respectively. Multilayer coated optics are most promising candidates for optical schemes at such sources, fulfilling extreme requirements in terms of figure and roughness errors, wavefront preservation, and stability, especially under near normal incidence conditions. However, the photon flux from short wavelength Free Electron Lasers is extremely high. Damage of the optics can be expected (even after a single shot exposure) which would limit the performance of the multilayer optics. Thus radiation resistivity of such coatings must be studied.

We have carried out research on the flux resistivity of a MoSi multilayer for radiation of 4.7 nm wavelength by means of exposures at FLASH – Free electron LASer in Hamburg. Samples were irradiated at different intensity levels with single and multiple shots. Morphological and structural surface changes were measured with phase-contrast microscopy, atomic force microscopy and scanning transmission electron microscopy. The exposure to the single pulses of intensity higher than the damage threshold leads to surface modifications similar as in case of previous experiments at longer wavelength [1]. In case of the multiple shot exposures, sample's damage was observed for radiation intensities lower than the damage thresholds for single pulses. Moreover, while the main damage mechanism was similar – atomic diffusion at the interfaces and formation of molybdenum silicides – the changes and their dependency on the incidence radiation fluence were found to be very different from the single shot exposures. Experimental data and the physical processes related to the observed structural changes will be discussed. The results are important for the design and further development of the optical coatings for the new generation of the short wavelength light sources, not only for the multilayers but for the single metallic layer coatings as well.

Acknowledgments: The authors wish to thank the staff of FLASH at DESY, Hamburg, Germany for supplying the beam time at FLASH. This work was partly supported by the Polish National Science Center (Grant No. DEC-2011/03/B/ST3/02453), the European

Regional Development Fund within the Innovative Economy Operational Programme 2007-2013 No POIG.02.01-00-14-032/08, the Foundation for Fundamental Research on Matter (Stichting voor Fundamenteel Onderzoek der Materie, FOM), the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO).

[1] A. R. Khorsand et al., Opt. Express 18, 700 (2010)

8777-16, Session 4

Results from single shot grazing incidence hard x-ray damage measurements conducted at the SACLA FEL

Andrew Aquila, Cigdem Ozkan, European XFEL GmbH (Germany); Ryszard Sobierajski, Institute of Physics (Poland); Vera Hájková, Tomas Burian, Jaromír Chalupsky, Libor Juha, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Michael Störmer, Helmholtz-Zentrum Geesthacht (Germany); Haruhiko Ohashi, Japan Synchrotron Radiation Research Institute (Japan) and RIKEN (Japan); Takahisa Koyama, Kensuke Tono, Japan Synchrotron Radiation Research Institute (Japan); Yuichi Inubushi, Makina Yabashi, RIKEN (Japan); Harald Sinn, Thomas Tschentscher, Adrian P. Mancuso, European XFEL GmbH (Germany); Jérôme Gaudin, Univ. Bordeaux 1 (France)

With the development of hard X-ray free electron lasers, there is a pressing need to experimentally determine the single shot damage limits of presently used and potentially future optical coating materials. To this end we present damage results, and analysis of threshold limits, from grazing incidence geometry experiments conducted at the Spring-8 Angstrom Compact free electron LAser (SACLA) on carbon, boron carbide, ruthenium, silicon, and a bilayer of boron carbide on ruthenium at 5.5, 7 and 12 keV photon energies.

8777-17, Session 5

Thermal effects on Co/Mo2C multilayer mirrors studied by soft x-ray standing wave enhanced photoemission spectroscopy

Angelo Giglia, Lab. Nazionale TASC (Italy); Subhrangsu Mukherjee, North Carolina State Univ. (United States); Nicola Mahne, Sincrotrone Trieste S.C.p.A. (Italy); Stefano Nannarone, Univ. degli Studi di Modena e Reggio Emilia (Italy); Philippe Jonnard, Karine Le Guen, Jean-Michel André, Yanyan Yuan, Univ. Pierre et Marie Curie (France); Zhanshan Wang, Jingtao Zhu, Tongji Univ. (China)

Here is presented the spectroscopic study of the evolution of the first buried interfaces of a B4C capped Co/Mo2C multilayer mirror induced by thermal treatment up to 600°C. This kind of study is typically performed to simulate the response of multilayer optics working in extreme conditions, as for instance when irradiated by new high brilliance sources as Free Electron Lasers. In fact the efficiency of multilayers is strictly related to the optical contrast between the alternating high and low density layers, and then to the degree of interdiffusion and the creation or evolution of interface compounds. The analysis has been performed at the Co L23 edge with different soft x-ray spectroscopic techniques including diffuse and specular reflectivity, total electron and fluorescent yield at the BEAR beamline at Elettra (Trieste) (http://www.elettra.trieste.it/elettra-beamlines/bear.html). The presentation is focused on the spectroscopic results obtained by soft x-ray standing wave enhanced photoemission (XSW) from the Mo 3d, B 1s, C 1s, O 1s core levels by using a photon energy close to the Co L23 edge and corresponding to the first Bragg peak of the multilayer. The experimental results have been compared with simulations to obtain information both on the chemical state (e.g. oxidation state) and interface morphology in terms of profiles of distribution of elements and interdiffusion of B4C and Mo and their relative oxides at the interface region. In summary it is possible to conclude in favour of a good stability of the multilayer in the temperature range investigated. A fact confirmed by the good performance in terms of reflectivity. The results confirm the use of XSW for these kind analysis of multilayer optics.

8777-18, Session 5

Fragmentation of clusters and recombination induced by intense and ultrashort x-ray laser pulses

Nicusor Timneanu, Bianca S. Iwan, Jakob Andreasson, Magnus Bergh, Marvin Seibert, Uppsala Univ. (Sweden); Christoph Bostedt, Sebastian Schorb, Heiko Thomas, Daniela Rupp, Tais Gorkhover, Marcus Adolph, Thomas Möller, Technische Univ. Berlin (Germany); Ahmed Helal, Kay Hoffmann, Nirmala Kandadai, John W. Keto, Todd Ditmire, The Univ. of Texas at Austin (United States); Janos Hajdu, Uppsala Univ. (Sweden)

Understanding the ultrafast dynamics of matter under extreme conditions is relevant for structural studies and plasma physics with X-ray lasers. We used the pulses from free-electron lasers (FLASH in Hamburg and LCLS in Stanford) to trigger X-ray induced explosions in atoms (Xe), molecules (CH4 and CD4) and their clusters. The explosion dynamics depends on cluster size and intensity of the X-ray pulse, and the results indicate a transition from Coulomb explosion to hydrodynamic expansion with increasing size or increasing pulse intensity. In methane clusters experiments at FLASH, the time-of-flight spectrometry shows the appearance of molecular adducts which are the result of molecular recombination between ions and molecules. The recombination depends on the cluster size and the expansion mechanism and becomes significant in larger clusters. In Xenon cluster experiments at the LCLS, measurements of the ion charge states in clusters suggest a formation of Xe nanoplasma which expands hydrodynamically. The dominance of low charge states is due to three-body recombination processes involving electron and Xe ions, and it depends on the X-ray intensity and nanoplasma formation.

8777-19, Session 6

Study of high-dose x-ray radiation damage of silicon sensors *(Invited Paper)*

Robert Klanner, Eckhart Fretwurst, Univ. Hamburg (Germany); Ioana Pintilie, National Institute for Materials Physics (Romania); Joern Schwandt, Jiaguo Zhang, Univ. Hamburg (Germany)

The high intensity and high repetition rate of the XFEL, the European X-ray Free-Electron Laser presently under construction in Hamburg, results in X-ray doses of up to 1 GGy in silicon sensors for 3 years of operation. Within the AGIPD Collaboration the Hamburg group has systematically studied X-ray-radiation damage using test structures and segmented sensors fabricated on high-ohmic n-type silicon. MOS Capacitors and Gate-Controlled Diodes from 4 vendors with different crystal orientations and different technological parameters, as well as strip sensors have been irradiated in the dose range between 10 kGy and 1 GGy. Current-Voltage, Capacitance/Conductance-Voltage and Thermal Dielectric Relaxation Current measurements were used to extract oxide-charge densities, interface-trap densities and surface-current densities as function of dose and annealing conditions. The results have been implemented into TCAD simulations, and the radiation performance of strip sensors and guard-ring structures simulated and compared to experimental results. Finally, with the help of detailed TCAD simulations, the layout and technological parameters of the AGIPD pixel sensor have been optimized. It is found that the optimization for sensors exposed to high X-ray doses is significantly different than for non-irradiated sensors, and that the specifications of the AGIPD sensor can be met. In 2012 sensors have been ordered, their delivery is planned for early 2013, and first results on a comparison between simulations and measurements will be presented.

8777-20, Session 6

X-ray laser-induced damage to inorganic scintillator materials

Tomas Burian, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Jérôme Gaudin, Cigdem Ozkan, European XFEL GmbH (Germany); Jaromír Chalupsky, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Sasa Bajt, Deutsches Elektronen-Synchrotron (Germany); Ludek Vysín, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Nicola Coppola, Shafagh Dastjani Farahani, European XFEL GmbH (Germany); Henry N. Chapman, Deutsches Elektronen-Synchrotron (Germany); Vera Hájková, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Marion Harmand, Institut National de la Recherche Scientifique (Canada); Libor Juha, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Marek Jurek, Institute of Physics (Poland); Rolf Antonie Loch, FOM Institute DIFFER (Netherlands); Jacek Krzywinski, SLAC National Accelerator Lab. (United States); Stefan Möller, Univ. Osnabrück (United States); Mitsuru Nagasono, RIKEN (Japan); Harald Sinn, European XFEL GmbH (Germany); Ryszard Sobierajski, Institute of Physics (Poland); Joachim Schulz, European XFEL GmbH (Germany); Sven Toleikis, Kai Tiedtke, Deutsches Elektronen-Synchrotron (Germany); Thomas Tschentscher, European XFEL GmbH (Germany)

Results are reported related to investigation of the interaction of soft x-ray ultra-short laser pulses with various inorganic scintillator materials carried out at the FLASH facility. Three samples, i.e., Ce:YAG, PbWO4, and ZnO were exposed to single 4.6-nm(± 1 nm) laser pulses of variable energy (up to 12 ?J) under normal incidence conditions. The effective beam area of 22 µm2 was determined by the analysis of ablated surface of poly(methyl methacrylate) - PMMA. Using various microscopy techniques such as differential interference contrast (DIC) and atomic force microscopy (AFM), damaged areas on the surface of scintillator samples were analyzed and measured. The single-shot damage threshold fluence was determined for each of these materials. The Ce:YAG sample seems to be the most radiation-resistant at this wavelength as its damage threshold was determined to be as high as 418 ± 11 mJ/cm2. Contrary to that, the PbWO4 sample exhibited the lowest radiation resistance with the threshold fluence of 119 ± 9 mJ/cm2. The threshold for ZnO was found to be 252 ± 9 mJ/cm2.

8777-21, Session 7

Experimental study of dynamics of solids exposed to intense and ultrashort radiation *(Invited Paper)*

Claude Fourment, François Deneuville, Univ. Bordeaux 1 (France)

Solid material damaging induced by intense and short electromagnetic wave is accompanied by structural modifications, as solid/solid phase transition, solid/liquid transition or ablation. In such interaction, the energy is mainly absorbed by electrons, increasing Te, and then transferred to the lattice at the 10 ps time scale. This out of equilibrium physics is the subject of intense experimental and theoretical work, rising fundamental questions about the thermal or non thermal nature of phase transition, the softening or hardening of bonds, and competition between thermal ablation and coulomb explosion.

An experimental technique, based on pump-probe interfero-polarimetry in reflection, is presented. It allows measuring the reflectivity and phase shift of an optical probe reflecting on the sample, in both P and S polarization directions, with a sub-100 fs time resolution. Accuracy on phase shift and reflectivity is 10 mrad and 1%, respectively. These quantities are dependant on both the sample optical properties (dielectric function) and the hydrodynamics of the heated sample. Careful comparison of signals in P and S polarization allows distinguishing between optical properties and hydrodynamics contributions. Optical properties give information about electron dynamics which drive the damage formation, mainly free-electron density and collisionnality. Hydrodynamics includes sample surface motion and electron density profile, at the nanometer scale.

This technique was employed to study damage on metals and dielectrics induced by infrared ultrashort laser (800 nm, 30 fs, ~1 J/cm?), and was demonstrated to be operated in XFEL environment.

8777-22, Session 7

A new method of determination of ablation threshold contour in the spot of focused EUV laser beam of nanosecond duration

Karel Kolacek, Jiri Schmidt, Jaroslav Straus, Oleksandr Frolov, Vaclav Prukner, Radek Melich, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic)

It is well known that at interaction of Extreme Ultraviolet Radiation (EUV) with a surface it is possible – according to local fluency - to distinguish two main regions: the desorption region (when efficiency eta of removing particles is <10%), and the ablation region (when efficiency eta ~ 100%). In this case, the ablation threshold determination is very simple and relatively accurate. It was e.g. shown that with the help of mapping of morphology of the ablation-dug-craters it is possible to determine the fluency distribution in/near the beam focus. However, recently we found [1] that (1) the desorption efficiency eta for nanosecond pulses is much higher than for femtosecond ones and spans from zero at the periphery imprint to ~90% at the ablation threshold; this extremely complicates the ablation threshold determination; (2) the direct nano-structuring of solid surfaces is possible only in the desorption region (e.g. the diffraction pattern generated in windows of in-proximity-standing-grid [2] is visible only in these parts of laser-beam-spot, which correspond to the desorption region). This prompted us to use this nano-patterning for determination of ablation threshold contour. The best possibility seems to be covering the laser beam spot by interference pattern. For that, it was necessary to develop a new type of interferometer, which (a) provides as dense interference pattern as possible, (b) uses practically all the energy of laser beam, (c) works with focused beams. Such interferometer has been designed. It is a modification of double-Lloyd mirror interferometer, but one of its mirrors is laterally shifted. Both mirrors have an ellipsoidal shape. Due to that, each of these mirrors focuses its part of laser beam to a separate focus. Both foci are placed close together and both beam-parts before reaching their foci intersect each other. In the intersection region, a dense interference pattern can be detected (e.g. by imprinting it into the target surface). The multilayer mirror coating has been designed to yield 1:1 beam intensity. Such interferometer has been tested by Zemax software to check that the interference pattern is really generated. The similar tests have been made even for non-ideal mirror surface and for non-ideal mirror positions to determine the mirror production and mirror adjustment tolerances.

Acknowledgments. This research has been supported by the Ministry of Education, Youth, and Sports of the Czech Republic (contract LA08024).

References.

[1] K.Kolacek, J.Straus, J.Schmidt, O.Frolov, V.Prukner, R.Melich, A. Choukourov, J.Sobota, T.Fort, Direct nano-structuring of solid surface by extreme ultraviolet Ar8+ laser, 57th International Conference on Electron, Ion, and Photon Beam Technology and Nanofabrication, Hilton Waikoloa Village, Waikoloa, Hawaii, USA, May 29 – June 1, 2012, Program Guide, Paper P06-6, to be published

[2] K.Kolacek, J.Straus, J.Schmidt, O.Frolov, V.Prukner, A.Shukurov, V.Holy, J.Sobota, T.Fort, Nano-structuring of solid surface by extreme ultraviolet Ar8+ laser, Laser and Particle Beams 30 (2012), 01, 57-63

8777-23, Session 7

On the properties of (inverse) fluence scan

Jaromír Chalupsky, Tomas Burian, Libor Juha, Vera Hájková, Institute of Physics, AS CR (Czech Republic); Tomas Polcar, Faculty of Electrical Engineering, Czech Technical University (Czech Republic); Jerome Gaudin, Univ. Bordeaux, CEA, CNRS, CELIA (France); Ryszard Sobierajski, Institute of Physics, Polish Academy of Sciences (Poland); Mitsuru Nagasono, Makina Yabashi, RIKEN/SPring-8 (Japan)

We present an extended theoretical background of the so called fluence scan (f-scan or F-scan) method which is currently being used for offline focused short-wavelength (XUV, soft and hard X-ray) laser beam characterization [1]. The method exploits ablative imprints in various solids to visualize iso-fluence beam contours at different fluence and/or clip levels. By varying the pulse energy an f-scan curve (clip level as a function of the contour area) can be generated for a general non-Gaussian beam. The fluence scan method greatly facilitates the analysis of non-Gaussian beams as the f-scan function contains important information about energy distribution within the beam profile. Here we discuss fundamental properties of the f-scan function and its inverse (if-scan or iF-scan) and elucidate how it is related to the effective area, energy distribution, and to the so called Liu's plot [2]. A new method of effective area evaluation based on weighted inverse f-scan fit is introduced in this paper and applied to real data obtained at SCSS (Spring-8 Compact SASE Source) facility.

[1] J. Chalupsky, J. Krzywinski, L. Juha, V. Hájková, J. Cihelka, T. Burian, L. Vysín, J. Gaudin, A. Gleeson, M. Jurek, A. R. Khorsand, D. Klinger, H. Wabnitz, R. Sobierajski, M. Störmer, K. Tiedtke, S. Toleikis, "Spot size characterization of focused non-gaussian X-ray laser beams," Opt. Express 18, 27836 (2010).

[2] J. M. Liu, "Simple technique for measurements of pulsed Gaussian-beam spot sizes," Opt. Lett. 7, 196 (1982).

8777-24, Session 7

RF plasma cleaning of mirror surfaces: characterization, optimization, and surface physics aspects of plasma processing *(Invited Paper)*

Eric J. Pellegrin, Igors Sics, Carlos Perez Sempere, Juan Reyes Herrera, CELLS-ALBA (Spain); Vincent L. Carlino, Ibss Group, Inc. (United States)

In this study, we present the results from an analysis of the various aspects of the RF plasma cleaning process for the removal of graphitic carbon contamination layers deposited on different test objects. After determining the optimum parameters for a time-minimized cleaning process using different plasma sources as well as feedstock gases, a special emphasis has been put on the characterization of the cleaned surface (Au, Ni, Rh) both in their pristine as well as in their cleaned state. This includes the physical as well as the chemical properties of the surfaces involved.

Last but not least, an effort has been made to characterize/monitor the RF plasma during the cleaning procedure in order to allow for an improved process control.

8777-25, Session 7

Refurbishment of damaged multilayer collector mirrors for EUV lithography *(Invited Paper)*

Torsten Feigl, Marco Perske, Hagen Pauer, Tobias Fiedler, Sergiy Yulin, Norbert Kaiser, Fraunhofer-Institut für Angewandte Optik und Feinmechanik (Germany); Norbert R. Bowering, Cymer, Inc. (Netherlands); Kay Hoffmann, Cymer, Inc. (United States)

Multilayer mirrors for extreme ultraviolet lithography at 13.5 nm face stringent demands for high reflectance, long-term stability, and optimal imaging properties. In addition, production time and cost are of crucial importance. Beside others the EUV source power and lifetime of EUV source collector mirrors is still one of the key challenges for EUV lithography today.

Inside a source-collector-module of a high-power EUV source the distance between the laser-produced plasma and the multilayer-based collector mirror is a few hundred millimeters only. In the harsh source environment the collector surface and the multilayer volume face EUV and out-of-band radiation as well as continuous ion, neutral and particle bombardment. Although great progress has been made during the last years the collector lifetime is still limited to several months of operation. Damaged multilayer collector mirrors need to be refurbished at the end of their lifetime. Fraunhofer IOF and Cymer have developed cost-effective refurbishment technologies of multilayer-based near normal incidence collector mirrors for high-power laser-produced plasma sources. This paper summarizes the latest strategies and improvements.

Today the collector mirror lifetime is primarily limited by deposition of tin and degradation of the upper layers of the coating causing a reduction of EUV reflectance at 13.5 nm. At the end of their lifetime the collector mirrors need to be replaced with refurbished collectors. In the past several technologies have been used to refurbish multilayer-based LPP collectors. Complete multilayer stripping, re-polishing and re-coating of used collectors as well as maintaining all or most of the initial multilayer coating are suitable techniques to refurbish damaged multilayer collector mirrors. Using different refurbishment approaches the initial EUV reflectance at 13.5 nm can be fully recovered without any reflectance loss. The paper discusses different LPP collector refurbishment strategies and presents the recent status on collector refurbishment techniques.

8777-27, Session PS

Study of radiation hardness of silicon photodiodes after exposure to EUV and x-ray radiation

Vladimir Zabrodsky, Pavel Aruev, Vladimir Filimonov, Nikolai A. Sobolev, Evgeniy Sherstnev, Ioffe Physico-Technical Institute (Russian Federation); Anton D. Nikolenko, Denis Ivlyushkin, Valery F. Pindyurin, Nikita Shadrin, Artem Soldatov, Mikhail Mashkovtsev, Budker Institute of Nuclear Physics (Russian Federation)

This experimental work is a continuation of the study of radiation hardness of silicon photodiodes [1,2], which are used for metrology and scientific research.

The following well-known XUV detectors were studied: silicon n-p photodiodes [3] and silicon p-n photodiodes [4,5]. It should be mentioned that the entrance windows of n-p photodiodes are made of oxynitride, while those of p-n photodiodes are composed mostly of boron and silicon.

Within the framework of the present work, silicon photodiodes were exposed to radiation of three spectrum regions with following quantum energies: 15-100 eV, 100-2000 eV, and 2-10 keV. An n-p diode and a p-n one were irradiated in each of the three parts of the spectrum. In total, six silicon photodiodes were investigated. The spatial profile of detector response and current-voltage characteristic were studied for all silicon photodiodes exposed to radiation of the EUV and x-ray spectral ranges. Besides, the response spatial profile was studied at 355 nm for all the six photodiodes irradiated.

It was shown that the investigated silicon p-n photodiodes have a higher hardness to the effects of radiation of the EUV and x-ray spectral ranges.

Presented is a feasible way of express imaging of some active area of a photodiode exposed to radiation of the EUV and x-ray spectral ranges. This method provides additional information, using which one can verify the methodology of the experiment, namely, the physical size of the EUV/x-ray beam used for dose accumulation.

REFERENCES

1. P.N. Aruev et al. / Nuclear Instruments and Methods in Physics Research A 603 58–61 (2009).

2. V.V. Zabrodsky et al. // Technical Physics Letters, (2012), Vol. 38, No. 9, pp. 812–815.

3. R. Korde, J. S. Cable, and L. R. Canfield, IEEE Trans. Nucl. Sci. 40, 1655–1659 (1993).

4. F. Scholze, R. Klein, R. Müller, Metrologia 43, S6-S10 (2006).

5. Zabrodsky V.V. et al. // Proceeding of the 9th ISMTII, Sankt-Petersburg, June 2009, pp. 3-243 – 3-247.

SPIE Optics+ Optoelectronics

8777-28, Session PS

Electron kinetics in liquid water excited by a femtosecond VUV laser pulse

Klaus Huthmacher, Technische Univ. Kaiserslautern (Germany); Nikita A. Medvedev, Ctr. for Free-Electron Laser Science (Germany); Bärbel Rethfeld, Technische Univ. Kaiserslautern (Germany)

We model numerically the interaction of an ultrashort VUV laser pulse with liquid water.

Liquid water is treated either as dense water vapor or as a semiconductor with a band structure. For the laser pulse we assume an photon energy of 100 eV and a gaussian shape with a FWHM of 10 fs.

To track each free electron and its collisions event by event, we use an extended Monte Carlo method [1]. First, we calculate the realized penetration depth of the photons.

Next, we compute the cross sections for the free electrons referring to ionization and elastic collisions. Further, we evaluate mean free paths of these electrons, and finally we get the energy loss due to elastic collisions or the energy transfer to secondary electrons due to ionization. All the secondary electrons are included in the calculations in the same manner. This approach allows us to describe a transient non-equilibrium behavior of irradiated water on femtosecond timescales.

We present transient electron energy distributions and a time resolved energy transfer, i.e.: the changing kinetic energy of excited electrons, the increasing of the energy of holes, and excitation of water molecules via elastic collisions. We compare results obtained with different models for the energy levels in liquid water: either assuming dense water vapor or an amorphous semiconductor with a band gap. Furthermore, we exhibit a time resolved description of the total amount of electrons to show their rapid increase in numbers.

[1] N. Medvedev and B. Rethfeld, New Journal of Physics 12 (2010) 073037

8777-29, Session PS

Characterizing the focus of a multilayer coated off-axis parabola for FLASH beam at ? = 4.3 nm

Adam F. Leontowich, McMaster Univ. (Canada); Andrew Aquila, European XFEL GmbH (Germany); Francesco Stellato, Richard Bean, Holger Fleckenstein, Deutsches Elektronen-Synchrotron (Germany); Mauro Prasciolu, Istituto Nazionale per la Fisica della Materia (Italy); Mengning Liang, Daniel P. De Ponte, Deutsches Elektronen-Synchrotron (Germany); Anton Barty, Lawrence Livermore National Lab. (United States); Feng-lin Wang, Deutsches Elektronen-Synchrotron (Germany); Jakob Andreasson, Janos Hajdu, Uppsala Univ. (Sweden); Henry N. Chapman, Sasa Bajt, Deutsches Elektronen-Synchrotron (Germany)

The range over which the Free electron LASer in Hamburg (FLASH) at DESY can operate in the fundamental continues to expand. In 2012, wavelengths just shorter than 4.4 nm have been made available to general users. This puts FLASH inside the "water window", a region where contrast between hydrated biological samples and water is optimal. We fabricated a normal incidence off-axis parabola coated with a Sc/B4C/Cr multilayer to focus the FLASH beam at 4.3 nm. For diffraction limited focus very tight specifications on figure and finish of the substrate have to be met. In addition, the multilayer coating has to satisfy Bragg's Law at every point within the clear aperture; the period must vary across the aperture to achieve the highest efficiency and resolution.

Beam imprints (craters) in poly(methyl methacrylate) were used to characterize the focusing properties of this optic at FLASH and to align the optic to achieve the smallest focused beam spot. A novel optical microscope was constructed to analyze the craters online, avoiding the need to vent the chamber after each alignment adjustment, thereby reducing the time needed to find the best focus. The craters were later analyzed offline using an atomic force microscope. These images revealed raised edges around the craters and ablated material extending radially in all directions. These features are a potential source of error for the beam profile measurement. The effectiveness of a post-exposure development technique at removing this material was investigated.

8777-30, Session PS

King´s College LPP X-ray source design

Alan G. Michette, Radhwan Alnaimi, King's College London (United Kingdom)

The objective of this work is to design and build a source that is to be used for such purpose and to optimize multilayer structures, in order to use the source output as efficiently as possible. Measurements is using King´s College Nd -YAG laser with fundamental wave length 1064 nm (IR), doubled frequency 532 nm (Green), tripled 355 nm (UV) and pulse length of about 800 PS. Target material is Mylar tape, containing mainly carbon. Mylar is much cheaper than other targets, easy to get and has many benefits as explained below. New cubic versatile vacuum chamber and a set of computer controlled stage motors are used which allows a suitable scanning transmission microscopy of the x-ray source.

8777-58, Session PS

Laser ablation of amorphous SiO2 by ultrashort pulses of XUV free electron laser

D. Klinger, R. Sobierajski, E. Lusakowska, J.B. Pelka, D. Zymierska, Institute of Physics, Polish Academy of Sciences (Poland); T. Burian, J. Chalupský, Institute of Physics, Czech Academy of Sciences and Czech Technical Univ. in Prague (Czech Republic); V. Hájková, Institute of Physics, Czech Academy of Sciences (Czech Republic); A.J. Gleeson, CCRLC/ Daresbury Lab. (United Kingdom); S. Hau-Riege, Lawrence Livermore National Lab. (United States), L. Juha, Institute of Physics, Czech Academy of Sciences (Czech Republic); A.R. Khorsand, Dutch Institute for Fundamental Energy Research (Netherlands); J. Krzywinski, SLAC National Accelerator Lab. (United States); R. London, Lawrence Livermore National Lab. (United States); S. Moeller, SLAC National Accelerator Lab. (United States); M. Nagasono, RIKEN/Spring-8 (Japan); H. Sinn, European XFEL GmbH (Germany); K. Sokolowski-Tinten, Univ. of Duisburg-Essen (Germany); N. Stojanovic, K. Tiedtke, S. Toleikis, Deutsches Elektronen-Synchrotron DESY (Germany); T. Tschentscher, European XFEL GmbH (Germany); L. Vyšín, Institute of Physics, Czech Academy of Sciences and Czech Technical Univ. in Prague (Czech Republic), H. Wabnitz. Deutsches Elektronen-Synchrotron DESY (Germany)

Laser-induced damages in amorphous silicon dioxide were investigated by means of irradiation with free electron laser beam. The experiments were performed at Free electron LASer in Hamburg and SPRING-8 Compact SASE Source sources, operating in the XUV regime (wavelength range of 7nm÷60nm). Morphological and structural changes of surface were measured with interference-polarizing microscopy with Nomarski contrast and atomic force microscopy. The threshold fluency for variable laser wavelength were obtained from studies of the damage area as a function the laser beam fluence. Changes of surface morphology were studied to understand the mechanism of the interaction processes between laser beam and material. The influence of the energy diffusion/penetration on the damage thresholds was analyzed. The results are discussed regarding the problem of radiation damage of optical surfaces.

8777-31, Session 10

X-ray optic developments at NASA's MSFC *(Invited Paper)*

Carolyn Atkins, Univ. of Alabama in Huntsville (United States); Brian D. Ramsey, Kiranmayee Kilaru, Mikhail V. Gubarev, Stephen L. O'Dell, Ronald F. Elsner, Douglas A. Swartz, Jessica A. Gaskin, Martin C. Weisskopf, NASA Marshall Space Flight Ctr. (United States)

NASA's Marshall Space Flight Center (MSFC) has a successful history of fabricating optics for astronomical x-ray telescopes. In recent years optics have been created using electroforming replication for missions such as the balloon payload HERO (High energy replicated optics) and the rocket payload FOXSI (Focusing Optics x-ray Solar Imager). The same replication process is currently being used in the creation seven x-ray mirror modules (one module comprising of 28 nested shells) for the Russian ART-XC (Astronomical Rontgen Telescope) instrument aboard the Spectrum-Roentgen-Gamma mission and for large-diameter mirror shells for the Micro-X rocket payload.

In addition to MSFC's optics fabrication, there are also several areas of research and development to create the high resolution light weight optics which are required by future x-ray telescopes. Differential deposition is one technique which aims to improve the angular resolution of lightweight optics through depositing a 'filler' material to smooth out fabrication imperfections. Following on from proof of concept studies, two new purpose built coating chambers are being assembled to apply this deposition technique to astronomical x-ray optics. Furthermore, MSFC aims to broaden its optics fabrication through the recent acquisition of a Zeeko IRP 600 robotic polishing machine. This paper will provide a summary of the current missions and research and development being undertaken at NASA's MSFC.

8777-32, Session 10

Hybrid X-ray optical system for space astrophysics

Ladislav Pina, René Hudec, Vladimir Tichy, Czech Technical Univ. in Prague (Czech Republic); Adolf J. Inneman, Daniela Cerna, Jiri Marsik, Veronika Marsikova, Rigaku Innovative Technologies Europe (Czech Republic); Webster Cash, Ann F. Shipley, Benjamin R. Zeiger, Thomas D. Rogers, Univ. of Colorado at Boulder (United States)

In this work, we investigate a novel design of optical system for astrophysics. In addition, a new testing method in the X-ray laboratory was verified. The proposed optical system is composed of modules with Kirkpatrick-Baez configuration allowing usage of multi-foil mirrors arranged to parabolic profile. This system effectively uses a circular aperture, which is divided into petals. Individual petals consist of diagonally oriented KB cells with common focus. The hybrid optical system includes a set of rotationally symmetrical parabolic mirrors to achieve higher reflection efficiency of harder X-rays. New results are presented.

8777-33, Session 10

Ray-tracing study of the eROSITA telescope

Emanuele Perinati, Eberhard Karls Univ. Tübingen (Germany); Michael J. Freyberg, Max-Planck-Institut für Extraterrestrische Physik (Germany); Teresa Mineo, INAF-IASF (Italy); Andrea Santangelo, Chris Tenzer, Eberhard Karls Univ Tübingen (Germany)

We investigate by means of ray-tracing simulations the stray-light contamination at the focal plane of the eROSITA telescope to verify to what extent the efficiency of the baffle may be affected by the precision in positioning it above the mirrors and calculate the tolerance range.

8777-34, Session 10

Slumping of Si wafers at high temperature

Martin Mika, O. Jankovsky, P. Simek, Institute of Chemical Technology (Czech Republic); Radka Havlikova, Czech Technical Univ. in Prague (Czech Republic); Z. Sofer, Institute of Chemical Technology (Czech Republic); René Hudec, Ladislav Pina, Czech Technical Univ. in Prague (Czech Republic); Adolf J. Inneman, Rigaku Innovative Technologies Europe (Czech Republic); Libor Sveda, Czech Technical Univ. in Prague (Czech Republic); Veronika Semencova, REFLEX s.r.o. (Czech Republic)

Space X-ray imaging telescopes have delivered unique observations that have been significantly contributing to important discoveries of current astrophysics. For future telescopes with a larger collecting area and a better angular resolution, the limiting factor is their X-ray reflecting mirror array. Therefore, for the successful construction of future lightweight and highly reflecting X-ray mirrors, new cost-effective technologies and progressive materials are needed. Currently, the very promising materials are silicon foils which are commercially produced on a large scale. We focused on the plastic deformation of thin monocrystalline silicon foils, which was necessary for the precise thermal forming of the foils to 3D shapes. To achieve the plastic deformation, we applied forced slumping at temperatures from 1200 to 1400°C. The final shapes and the surface quality of the foils were measured using a Taylor Hobson contact profilometer and examined with an Atomic Forced Microscopy. We discuss the effects of temperature, applied slumping force, heat-treatment time, crystal orientation, and furnace atmosphere on the shape and surface quality of the formed foils.

8777-35, Session 10

Fast and simple algorithm for computer simulation of multi-foil optics

Vladimir Tichy, Czech Technical Univ. in Prague (Czech Republic)

The presented algorithm has been developed mainly for simulating of 1-D and 2-D Schmidt clone of lobster eye X-ray optics. The method is based on calculating of reflections of individual mirrors and it was consequently simplified using own mathematical formalism based on vector and complex numbers algebra. The presented method is extremely effective. Ideas how to apply it for another grazing incidence X-ray systems are persented.

8777-36, Session 10

NANOX - Proposed Nano-Satellite X-Ray Space Mission

Vladimir Tichy, Czech Technical Univ. in Prague (Czech Republic); Vojtech Simon, Astronomical Institute of the Academy of Sciences (Czech Republic); Marco Barbera, Università degli Studi di Palermo (Italy); René Hudec, Czech Technical Univ. in Prague (Czech Republic); Adolf Inneman, Rigaku Innovative Technologies Europe, s.r.o. (Czech Republic); Ladislav Pína, Czech Technical Univ. in Prague (Czech Republic)

The concept of nano-satellite space X-ray mission is presented. The goal of the mission would be mainly long-term monitoring of X-ray binaries laying in the center of the Galaxy. To achieve this goal, using of grazing incidence Schmidt lobster eye X-ray optics is supposed. Experimental tests of specimen of the optics showing techonoligical feasibility of the mission are presented. Total dimensions and focal length of the proposed X-ray telescope allow its boarding on the 6-U size nano-satellite.

8777-37, Session 11

Concepts for rapid tuning and switching of X-ray energies

Werner H. Jark, Sincrotrone Trieste S.C.p.A. (Italy); Arndt Last, KIT/IMT (Germany)

I proposed recently, that the Clessidra x-ray lens can be operated such that the photon energy can be tuned in a fixed exit slit [W. Jark, JSR 19, 492-496 (2012)]. The Clessidra lens is formed of many tiny prisms, which are arranged in the form of a large prism. The focusing is achieved as the number of prisms increases with increasing distance from the lens optical axis. Even though originally the Clessidra lens was proposed as a kinoform for the focusing of x-rays, one can also operate it as an assembly of many independent microlenses. Then no particular requirement exists for the spatial coherence of the incident radiation. And also the precise lens alignment is not an issue anymore. On the contrary by rotating the lens out off alignment, one can then tune the photon energy in a fixed exit slit. For this purpose the structure with sufficiently wide prisms will have to be rotated around an axis in the plane of incidence and perpendicular to the incident radiation. As the lens then functions exclusively as a refracting object it can also be used in combination with laboratory x-ray sources.

The Clessidra lenses have rather limited dimensions and consequently the proposed tuning can be realised with a simple rotation, which can be performed even with higher rotational speeds. I will thus discuss in this contribution concepts, in which a rapid switching between two photon energies can be realised for different experimental techniques.

8777-38, Session 11

The impact of novel 3-dimension diffraction optics development

Alexander Firsov, Maria Brzhezinskaya, Heike Loechel, Frank Siewert, Alexei Erko, Helmholtz-Zentrum Berlin für Materialien und Energie (Germany)

Availability of suitable diffractive VUV and X-ray optics is the basis of further breakthrough in measurement techniques, especially for time-resolved spectroscopy. The quality of achievable results depends first of all on the availability of high-quality optical components like gratings or diffractive focusing elements.

We focus on the development of new methods of time-resolved x-ray spectroscopy based on novel 3D diffractive optical elements (DOE) with a unique combination of properties. Such optical elements are of high interest for application in modern synchrotron facilities, Free Electron Lasers (FELs) and laboratory facilities with high harmonic generators (HHG). The project includes the development of theory and technology of the optics, optics metrology, as well as application of this optics to atomic, molecular and condensed matter physics. Having been successfully implemented into an X-ray fs-beamline at BESSY II in soft X-ray range, DOE could be an important device in upcoming new high brilliance X-ray sources such as Free Electron Lasers (FELs). The reduction of the number of optical elements in a beamline would allow the highest possible transmission and satisfy the purpose of conserving the unique properties of FELs such as their high coherence.

Such elements are presently neither available nor under development at other research institutions.

This work was supported by the Marie Curie FP7-Reintegration-Grants within 7th European Community Framework Program (project No. PCIG10-GA-2011-297905) and the German-Russian cooperation on „Development and use of accelerator-driven photon sources“ (BMBF-Projekt No. 05K12CB4).

8777-39, Session 11

X-ray nanoprobe based on a refractive optic and x-ray coherent diffraction as a complex tool for ZrOx/SiO2 multilayer studying

Petr Ershov, European Synchrotron Radiation Facility (France) and Immanuel Kant Baltic Federal University (Russian Federation); Alexander Goikhman, Natali Klimova, Immanuel Kant Baltic Federal University (Russian Federation); Vyacheslav Yunkin, IMT RAS (Russian Federation); Mikhail Lyubomirskiy, Irina Snigireva, Anatoly Snigirev, European Synchrotron Radiation Facility (France)

Recent developments of high-brilliance, high energy and coherent x-ray sources, coupled with progress in x-ray focusing optic technologies[1] give an opportunity to a complex study of nanoscale objects. As a result the x-ray nanoprobe concept, when the focused x-ray beam is used like a probe, is under wide implementation in synchrotrons. The great advantage of the nanoprobe is a possibility of using methods based on an elastic, inelastic x-ray scattering and in an x-ray absorption without optical scheme reconstruction. Recently studies have been done on x-ray nanoprobe research of SOI heterostructures[2] and solar cells[3].

We used compound refractive lenses(CRL)[4] to create an x-ray nanoprobe which gave us the opportunity to perform a complex analysis of ZrOx/SiO2 multilayer(ML). We studied a ML consisting of six alternating ZrOx and SiO2 layers with 500 nm thickness and 1.5 mm lateral length. The ML was manufactured by Ion Beam Assisted Deposition(IBAD) technique in the Functional Nanomaterials Research and Educational Centre of Immanuel Kant Baltic University, Russia.

The experimental techniques which we carried out in a scanning regime are: X-ray Fluorescence(XRF) and X-ray Scanning Transmission Microscopy(XSTM). As a complementary technique to XSTM we used lensless coherent x-ray diffraction on the ML cross-section. Additionally we performed x-ray absorption spectra measurement of the ZrOx layer. The x-ray energies working region were near the Zr absorption edge (17-18 KeV) where theoretical SiO2 layer absorption is 105 times smaller than the ZrOx layer absorption. All measurements were conducted at the Micro-optics Test Bench of the ESRF ID6 beamline.

The result of our study demonstrates a possibility to produce sub-micron contrast imaging of a ML by x-ray fluorescence and x-ray abortion together with additional x-ray absorption spectra measurements and lensless x-ray coherent diffraction. We believe that an x-ray nanoprobe will be useful in ML research due to the opportunity of a complex analysis of the ML interfaces.

[1] A. Snigirev, I. Snigireva, M. Grigoriev, V. Yunkin, M. Di Michiel, G. Vaughan, V. Kohn, S. Kuznetsov, “High energy X-ray nanofocusing by silicon planar lenses”, Journal of Physics: Conference Series 186, 012072, 2009.

[2] A.Ying, B. Osting, I. Noyan, C. Murray, M. Holt and J. Maser., “Modeling of kinematic diffraction from a thin silicon film illuminated by a coherent, focused X-ray nanobeam”, J. Appl. Crystallogr. 43 (3), 587-595, 2010

[3] M.Bertoni,D. Fenning,M. Rinio,V. Rose,M. Holt,J. Maser and T. Buonassis,”Nanoprobe X-ray fluorescence characterization of defects in large-area solar cells”, Energy Environ. Sci., 4, 4252, 2011

[4] A. Snigirev, V. Kohn, I. Snigireva and B. Lengeler , “A compound refractive lens for focusing high-energy X-rays”, Nature, vol. 384, 49-51, 1996

8777-40, Session 11

X-Ray multilens interferometer based on planar refractive optics

Mikhail Lyubomirskiy, European Synchrotron Radiation Facility (France); Anatoly Snigirev, ESRF (France); Iraida Snigireva, European Synchrotron Radiation Facility (France); Viktor Kohn, Kurchatov Institute (Russian Federation); Vyacheslav Yunkin, Sergey Kuznetsov, IMT RAS (Russian Federation)

Refractive x-ray optics [1] can be used to purpose new interferometry techniques along with obvious focusing and imaging schemes. Recently a bilens interferometer based on planar refractive optics was proposed [2]. It consists of identical planar parallel lenses, which are divided by a distance less than a coherence length of a primary synchrotron beam. Two secondary coherent sources are arising under coherent illumination. Those sources generate a periodical interference pattern i.e. standing wave. The period of the standing wave depends on observation distance and varies from nanometres to microns.

To extend a bilens interferometer beam acceptance we have developed a multilens system, which uses more than two parallel lenses. The increasing of an acceptance allows raising intensity and contrast of the interference pattern at the expense of interference maxima compression. In comparison with the bilens interferometer, where the mechanism of a wave front formation is simple, a multilens system forms a more complicated interference pattern which can be described in the Talbot imaging concept.

The aim of this work is to study 6-lens interferometer optical properties. The 6-lens structures were manufactured on a Si substrate by the MEMS micro fabrication technology involving lithography and deep etching. The split distance between the lenses is 30 ?m. Study of interferometer properties were performed in the energy range of 12-24 keV at the ID6 beamline. The Si interferometer was mounted at a distance of 56 m from the source. Interference patterns were recorded with the high resolution x-ray CCD camera with a spatial resolution of approximately 1.3 ?m. To record the interference pattern at the fractional Talbot distances, the CCD camera was placed at the distance zn = z1 - zf = 290 cm, where z1 is lens to detector distance and zf is the lens focal distance. The measured fringe spacing was ? = 10.25 ?m at 12 keV. It is in very good agreement with the calculations. We believe that this new interferometry approach opens up new possibilities of developing precise X-ray nano-metrology and nano-diagnostic techniques.

[1] A. Snigirev, V. Kohn, I. Snigireva, B. Lengeler: A compound Refractive Lens for focusing High-Energy X-rays. Nature, 384, 49-51, 1996

[2] A. Snigirev, I. Snigireva, V. Kohn, V. Yunkin, S. Kuznetsov, M. Grigoriev, T. Roth, G. Vaughan, C. Detlefs: X-Ray nanointerferometer based on Si refractive bilenses. Phys. Rev. Letters 103, 064801, 2009.

8777-41, Session 11

X-ray Refractive optic as a Fourier transformer for high resolution diffraction

Petr Ershov, Immanuel Kant Baltic Federal University (Russian Federation) and ESRF (France); Serguei Kuznetsov, IMT RAS (Russian Federation); Irina Snigireva, ESRF (France); Vyacheslav Yunkin, IMT RAS (Russian Federation); Alexander Goikhman, Immanuel Kant Baltic Federal University (Russian Federation); Anatoly Snigirev, ESRF (France)

The third-generation synchrotron together with refractive optics has open up new possibilities in the study of microscopic objects. Apart from the excellent microfocusing and imaging applications, one of the most notable and useful properties of compound refractive lenses(CRL) [1] is it's intrinsic ability to perform one or two dimensional Fourier transforms. These properties in the case of hard X-rays has been demonstrated theoretically [2] and experimentally [3]. Recently it has been shown that the small angle diffraction setup with CRL as a Fourier analyser has the microradian angular resolution. This new technique has been applied for studies of colloidal and photonic crystals [4].

In the present work we propose refractive optics as a Fourier transformer of high resolution x-ray crystal diffraction. In this case the wave transmitted through the object transforms into spatial intensity distribution at the observation plane according to the Fourier relations. CRL are well suited for the Fourier transform analysis in the hard X-ray energy range from 2 to 100 keV.

An alternative useful technique to study gratings on Si crystal is triple-crystal diffraction, where the wave transmitted through the object is the incident wave for the crystal-analyzer [5]. The advantages of Fourier transform of high resolution diffraction techique in comparison to conventional triple-crystal diffraction are: the possibility to observe a dynamic process (like surface acoustic waves[6]), possibility to provide scheme stability and the ability to quickly change the scheme to a diffraction microscopy regime.

Two types of samples had studied in Bragg reflection geometry: a grating made of strips of a thin SiO2 film on Si substrate and a grating made by profiling a Si crystal. Rocking curve of Si(111) Bragg reflection and corresponding Fourier patterns were analysed. The experiment was conducted at the ESRF BM5 and ID6 beamlines.

Further development of Fourier transform diffraction techniques based on refractive optics will complement a triple-crystal diffractometry results. This technique could be used to design an X-ray diffraction microscope similar to electron microscope where diffraction pattern can be switched to full-field image.

[1] A. Snigirev, V. Kohn, I. Snigireva and B. Lengeler , "A compound refractive lens for focusing high-energy X-rays", Nature, vol. 384, 49-51, 1996

[2] V. Kohn, I. Snigireva, A. Snigirev, "Diffraction theory of imaging with compound refractive lens", Optics Communications, vol. 216, 247-260, 2003.

[3] M. Drakopoulos, A. Snigirev, I. Snigireva, J. Schilling, "X-ray high resolution diffraction using refractive lenses", Applied Physics Letters, 86, 014102, 2005.

[4] A. Bosak , I. Snigireva, K. Napolskii and A. Snigirev, "High-Resolution Transmission X-ray Microscopy: A New Tool for Mesoscopic Materials", Adv. Mater., 22, 3256–3259, 2010.

[5] V.Aristov, S. Kuznetsov, A. Nikulin and A.Snigirev "X-ray diagnostics of 2D strain profiles in semiconductor crystals", Semiconductor Science and Technology, 7, A168-A170, 1992.

[6] D. Roshchupkin, D. Irzhak, A. Snigirev, I. Snigireva,L. Ortega and A. Sergeev, "Diffraction of a focused x-ray beam from La3Ga5SiO14 crystal modulated by surface acoustic waves", Journal of Applied Physics, 110, 124902, 2011.

8777-57, Session PS

Analytic investigation of Fourier-transform holographic magnetic imaging method based on the magneto-optical effect

Dong-Hyun Kim, Chungbuk National University (Korea, Republic of); Tae Kyu Kim, Pusan National University (Korea, Republic of); Jaehun Park, Pohang Accelerator Laboratory (Korea, Republic of); Djati Handoko, Chungbuk National University (Korea, Republic of)

Recently, numerous studies have been addressed to X-ray holography imaging [1], mostly motivated by the development of free electron laser, which opens a new possibility in exploration of ultrafast dynamics of charge, lattice, and spin with a femtosecond light pulse. On the other hand, conventionally, magneto-optical Kerr or Faraday effect has been used to investigate magnetic properties of ferromagnetic systems, particularly a film. The magneto-optical effect generally manifested in the visible wavelength ranges is not widely utilized in X-ray range[2] since the X-ray magnetic circular dichroism usually reveals better details. In the visible range, a Fourier-transform holographic imaging technique was well established. Here, we report our analytic and theoretical investigation of the Fourier-transform holographic magnetic imaging method based on the magneto-optical effect. Condition for the holography is found to kill the holographic signal in simple cases of using linear polarizations. Necessary polarization control required to form a magnetic image will be discussed in detail.

[1] S. Marchesini et al., Nature Photonics 2, 560 (2008).

[2] D.-E. Jeong et al., J. Kor. Phys. Soc. 46, 1180 (2005).

8777-42, Session 12

Adaptive X-ray optics development at AOA-Xinetics

Kevin M. Ezzo, Northrop Grumman Xinetics (United States); Charles F. Lillie, Lillie Consulting, LLC. (United States); David D. Pearson, Jeffrey L. Cavaco, Audrey D. Brooks, Northrop

Grumman Xinetics (United States); John Wellman, Metenco LLC (United States)

Grazing-incidence optics for X-ray applications require extremely smooth surfaces with precise mirror figures to provide well focused beams and small image spot sizes for astronomical telescopes and laboratory test facilities. The required precision has traditionally been achieved by time-consuming grinding and polishing of thick substrates with frequent pauses for precise metrology to check the mirror figure. More recently, substrates with high quality surface finish and figures have become available at reasonable cost, and techniques have been developed to mechanically adjust the figure of these traditionally polished substrates for ground-based applications. The beam-bending techniques currently in use are mechanically complex, however, with little control over mid-spatial frequency errors. AOA-Xinetics has been developing been developing techniques for shaping grazing incidence optics with surface-normal and surface-parallel electrostrictive Lead magnesium niobate (PMN) actuators bonded to mirror substrates for several years. These actuators are highly reliable; exhibit little to no hysteresis, aging or creep; and can be closely spaced to correct low and mid-spatial frequency errors in a compact package. In this paper we discuss recent development of adaptive x-ray optics at AOAXinetics.

8777-43, Session 12

Active X-ray optics

René Hudec, Astronomical Institute of the ASCR, v.v.i. (Czech Republic) and Czech Technical University in Prague (Czech Republic); Adolf J. Inneman, Rigaku Innovative Technologies Europe (Czech Republic); Daniela Cerna, Rigaku Innovative Technologies (Czech Republic); Zdenek Hurak, Marek Hudec, Vladimir Tichy, Ladislav Pina, Czech Technical Univ. in Prague (Czech Republic)

We report on results of project in the direction of astronomical active X-ray optics. Various flat and thin substrates have been exploited and tested, as well as different piezo-elements and actuators. Several test mirrors and modules were assembled and tested in X-rays with clear demonstration of performance improvement upon applying active approach.

8777-44, Session 12

Water-window microscopy using compact, laser-plasma source based on Ar/He double stream gas-puff target

Przemyslaw W Wachulak, Andrzej Bartnik, Marcin Skorupka, Jerzy Kostecki, Roman Jarocki, Miroslaw Szczurek, Lukasz Wegrzynski, Tomasz Fok, Henryk Fiedorowicz, Military Univ of Technology (Poland)

Photon-based (bosonic-type) imaging at short wavelength vs. electron, or recently neutron, imaging has additional advantages due to different interaction of photons with matter and thus high resolution photon-based imaging is still of high interest to the scientific community.

In this work we try to combine the advantages of employing compact, laboratory type laser-plasma short wavelength source, based on Ar/He gas puff target, emitting incoherent radiation, with the "water-window" spectral range. This unique combination is highly suitable for biological imaging, and allows to develop a small size microscopy setup, which might be used in various fields of science and technology. Thus, in this paper we report for the first time on "water-window" desk-top microscopy setup employing a laser-plasma SXR source based on a double stream gas puff target and Wolter type-I objective. The system allows capturing magnified images of the objects with ~1 micron spatial resolution up to ~40?microns thickness and exposure time as low as 5 seconds.

For the SXR microscope Ar plasma was produced by focusing of the pumping laser pulses, from Nd:YAG laser (Eksma), with duration of 4 ns and energy of 0.74 J by an f = 25 mm focal length lens onto a gas puff target. EUV radiation from the plasma was collected and focused by an ellipsoidal, axi-symmetrical nickel coated condenser mirror, developed by Rigaku, Inc. The condenser is a broad-band optic, capable of efficiently reflecting radiation from the EUV range down to SXR region with energy cut-off of ~600 eV. To spectrally narrow the emission from argon plasma a 200 nm thick, 10 mm in diameter, free-standing titanium filter (Lebow) was used. Spectrally filtered radiation illuminated the sample. Then the sample was imaged onto a SXR sensitive back-illuminated, CCD camera (Andor) by a Wolter type-I reflective objective.

A detailed characterization and optimization of both the source and the microscope setups are presented and discussed.

8777-45, Session 12

Planned soft X-ray transmission microscope at the Czech Technical University in Prague

Vladimir Tichy, Petr Bruza, Radek Machán, Dalibor Pánek, Alena Semerádtová, Miroslava Vrbová, Czech Technical Univ. in Prague (Czech Republic)

The technological concept of proposed XUV microscope at FBMI of CTU in Prague is presented. The microscope is designed for exploring of biological samples. The microscope will operate as a common soft X-ray transmission microscope. It will operate at wavelength 2.88nm laying within the water window region. We suppose the spatial resolution in order of tens of nanometers will be achieved.

8777-46, Session 13

Spectral filtering optimization of a measuring channel of an X-ray broadband spectrometer

Benoit Emprin, Philippe Troussel, Bruno Villette, Commissariat à l'Énergie Atomique (France); Franck Delmotte, Lab. Charles Fabry (France)

Within the framework of its researches on Inertial Confinement Fusion (ICF), the "Commissariat à l'Énergie Atomique et aux Énergies Alternatives" (CEA) studies and designs advanced X-ray diagnostics in order to probe dense plasmas that will be produced in the future Laser MegaJoule (LMJ) facility. A new channel of a X-ray broad bandwidth diagnostic has been developed for the 2 - 4 keV spectral range. It uses a spectral filtering by using a multilayer mirror. This channel is composed by a filter, an non-periodical multilayer mirror and a detector. The design and realization of the optical coating mirror has been defined such as the reflectivity is above 15% in almost the entire bandwidth range 2 – 4 keV and lower than 2% outside.

The mirror is optimized for working at 1.9° grazing incidence. This study follows the one already made at 1.5° [1]. The mirror is coated with a stack of 121 chromium / scandium (Cr / Sc) non-periodic layers (between 0.6 nm and 9.3 nm) and a 3 nm thick top SiO_2 layer to protect the stack from oxidization. To control thin thicknesses of the non-periodical Cr / Sc multilayer mirror, we produced specific multilayer mirrors. These mirrors are coated with a thin layer of chromium or scandium between two periodical Cr / Sc multilayers. They are deposited on SiO_2 substrate with 0.3 rms roughness. The mirror and subnanoscale layers characterization were made at the "Laboratoire Charles Fabry" (LCF) with a grazing incidence reflectometer working with Cu K? radiation at 8.048 keV and at the synchrotron radiation facility SOLEIL on the hard X-ray branch of the "Metrology" beamline. The reflectivity of the mirrors as a function of the photon energy was obtained at 1.9° grazing angle in the Physikalisch Technische Bundesanstalt (PTB) laboratory at the synchrotron radiation facility Bessy II [2] on the X-ray channel from the laboratory. We get excellent results, there is a good agreement between LCF and SOLEIL measurements, the subscale layer thicknesses measurements are good and the periodic multilayer mirror is perfectly controlled (the measured thicknesses from LCF, PTB and SOLEIL are the same).

[1] F. Bridou et al. Nucl. Instru. & Meth. in Phys. Res. A 680 (2012) 69-74.

[2] M. Krumrey, G. Ulm. Nuclear Instruments and Methods A 467 (2001) 1175

8777-47, Session 13

Single and multi-channel Al-based multilayer systems for space applications in EUV range

Evgueni Meltchakov, Sébastien de Rossi, Lab. Charles Fabry (France); Raymond Mercier, Institut d'Optique Graduate School (France); Françoise Varnière, Lab. Charles Fabry (France); Arnaud Jérôme, Institut d'Optique Graduate School (France); Frédéric Auchère, Xueyan Zhang, Institut d'Astrophysique Spatiale (France); Marc Roulliay, L'Institut des Sciences Moleculaires d'Orsay (France); Franck Delmotte, Institut d'Optique Graduate School (France)

We will report on further development of reflecting multilayer coatings containing aluminum as low absorbing material for the extreme ultra-violet (EUV) applications, in particular for solar physics. Optimizations of multilayer design and deposition process have allowed us to produce Al-based multilayer coatings having relatively low interface roughness and a high reflectivity in the range from 17 to 40 nm. The EUV peak reflectance higher than 50 % between 17 and 21 nm and more than 40 % around 30 nm was measured with new three-material multilayers Al/Mo/SiC and Al/Mo/B4C at near-normal incidence [1]. We observed a rather good temporal stability of optical parameters of the multilayers over 4 years. Moreover, the multilayer structure remains stable upon heating to 350 °C.

We will discuss the optical properties of Al-based coatings with regard to the design of more complex multilayer structures operating as multi-channel optical systems, which reflect more than one wavelength and reject some others within the spectral range from 17 to 40 nm. Such systems with enhanced selectivity would provide a significant advance in optical performance of space instruments for the EUV imaging, which are also suffering from size and weight restrictions.

We will present various aspects of design, calculations and fabrication of single- and multi-channel multilayer mirrors made with a use of aluminum. We will show recent results of characterization of Al/Mo/SiC and Al/Mo/B4C multilayers by means of the EUV and X-ray reflectivity measurements.

[1] EUV reflectivity and stability of tri-component Al-based multilayers. E. Meltchakov, A. Ziani, F. Auchere, X. Zhang, M. Roulliay, S. De Rossi, Ch. Bourassin-Bouchet, A. Jérome, F. Bridou, F. Varniere and F. Delmotte. Proc. SPIE 8168, 816819 (2011)

8777-48, Session 13

Multilayer reflective polarizers for the far ultraviolet

Juan I. Larruquert, José A. Aznárez Candao, Luis Rodríguez de Marcos, José A. Méndez, Consejo Superior de Investigaciones Científicas (Spain); A. Marco Malvezzi, Univ. degli Studi di Pavia (Italy); Angelo Giglia, Lab. Nazionale TASC (Italy); Paolo Miotti, Fabio Frassetto, Univ. degli Studi di Padova (Italy); Giuseppe Massone, INAF - Osservatorio Astronomico di Torino (Italy); Stefano Nannarone, Univ. degli Studi di Modena e Reggio Emilia (Italy); Giuseppe Crescenzio, Gerardo Capobianco, Silvano Fineschi, INAF - Osservatorio Astronomico di Torino (Italy)

Polarimetry in the far ultraviolet (FUV) is a powerful tool for the interpretation of the role of the coronal plasma in the energy transfer processes from the inner parts of the Sun to the outer space. FUV polarimetry from space provides more accurate observations on the kinetics of the features and on local magnetic fields through the Doppler and Hanle resonant electron scattering effects. Particularly interesting lines for FUV polarimetry are H Lyman alpha (121.6 nm) and beta (102.6 nm), along with OVI lines at 103.2 and 103.8 nm. One key element to perform polarimetry measurements at these wavelengths is the need for efficient polarizers. The more standard polarizers for these wavelengths are crystal plates of transparent fluorides, namely MgF2 and LiF, working in reflection at Brewster angle. One limitation of these elements is their moderate reflectance at the non-extinguished component of the electric field, which results in a moderate polarizer efficiency.

Research is underway to develop efficient polarizers based on reflective multilayer coatings. First wavelength target is 121.6 nm. Bridou et al. (a) reported on efficient polarizers based on various coatings, including Al/MgF2 multilayers. We have obtained promising preliminary results with (Al/ MgF2)n multilayer polarizers. Polarizer designs based on up to four Al/MgF2 bilayers have been prepared. Their reflectance for both s (TE) and p (TM) polarization has been measured as a function of the angle of incidence and wavelength at BEAR beamline of ELETTRA synchrotron, in Italy. The analysis of the first results will enable refining the designs in order to make new series of polarizers with a higher efficiency. The deviation between design and experimental data is attributed to a low MgF2 packing density, to the possible presence of oxidation and/or contamination at the outer interface, and perhaps to the presence of non-abrupt interfaces. Further research will be conducted to better understand the microscopic structure of these multilayers. Future research will address the stability of these polarizers in relevant conditions for space optics.

(a) F. Bridou, M. Cuniot-Ponsard, J.-M. Desvignes, A. Gottwald, U. Kroth, M. Richter, "Polarizing and non-polarizing mirrors for the hydrogen Lyman-? radiation at 121.6 nm", Appl Phys A 102, 641–649 (2011).

8777-49, Session 13

Narrowband coatings for the 100-105 nm range

Luis Rodríguez de Marcos, José A. Méndez, Manuela Vidal-Dasilva, José A. Aznárez Candao, Juan I. Larruquert, Consejo Superior de Investigaciones Científicas (Spain)

Observations in the far ultraviolet (FUV) at wavelengths ~100-105 nm, which include 102.6 nm (H Lyman beta) and 103.2, and 103.8 nm (O VI lines), are expected to unveil fundamental information for solar physics and astrophysics. Often the intensity of those lines is weak, and they may be masked by more intense lines, such as H Lyman alpha at 121.6 nm for observations of the solar corona. Narrowband multilayers peaked in the ~100-105 nm have not been available because of the absorption of materials at these wavelengths along with a strong influence of contamination in this range. When efficient narrowband coatings are not possible, a solution is the use of coatings with high 100-105-nm reflectance and simultaneously low reflectance at the undesired wavelength, such as 121.6 nm.

High-reflective, narrowband coatings peaked at 100-105 nm have been developed. We have designed a four-layer system (Al/LiF/SiC/LiF) that results in efficient narrowband coatings peaked in the target range. The same system results in an efficient reflection/rejection ratio for the H Lyman beta/alpha, respectively. Normal reflectance was measured in the 50-200 nm spectral range. All samples showed a promising reflectance when fresh. Some sample aging was observed after months of storage in a desiccator, probably due to the effect of water vapors among other contaminants on the top layer (LiF). Various samples with slightly different film thicknesses were prepared in order to minimize the aging effect on the multilayer performance. The samples retained a narrowband performance over time. The reflectance at 121.6 nm, which was very low on fresh samples, showed a trend to increase over time, although keeping a high 102.6-to-121.6-nm reflectance ratio.

8777-50, Session 13

Optical performance, structure and thermal stability of Al/Zr multilayers working at above 17nm

Zhanshan Wang, Qi Zhong, Zhong Zhang, Jingtao Zhu, Tongji Univ. (China); Yuhong Bai, Changchun Institute of Optics, Fine Mechanics and Physics (China); Philippe Jonnard, Karine Le Guen, Jean-Michel André, Univ. Pierre et Marie Curie (France)

The optical performance, structure and thermal stability of periodic multilayer films containing zirconium (Zr) and silicon doped aluminum

(Al(1%wtSi)) or aluminum (Al(pure)) layers used as reflective mirrors working at above 17 nm were presented. The results show that the Al(1%wtSi)/Zr multilayer has the lower interfacial roughness and higher reflectivity, which also presents good thermal stability in the EUV region, than those of Al(pure)/Zr multilayer. However, there is a difference between the theoretical and experimental reflectivity of Al(1%wtSi)/Zr multilayer, which was explained on the basis of surface contamination, the inhomogeneous crystallization of aluminum, contamination in the multilayer, surface oxidized layer and interdiffusion between Al(1%wtSi) and Zr layers. Transmission electron micrograph images reveal that the interfacial roughness is associated to the Al and Zr crystallites. For less than 40 periods in the multilayer, the roughness components are smaller. For more than 40 periods, both surface and interfacial roughness increase with the period number. The thermal stability of Al(1%wtSi)/Zr multilayers is checked by annealing at temperatures from 100 °C to 500 °C in a vacuum furnace. As the results of grazing incident X–ray reflection show, the Al(1%wtSi)/Zr multilayers annealed up to 200 °C maintained the same initial multilayer structure as the as-deposited sample. From 300 °C, the amorphous Al–Zr alloy has transformed to the polycrystalline ZrAl3 alloy in the interface, but do not destroy the multilayer structure completely. The effect of different reaction temperatures, the formation of variable materials between Al and Zr layersand the transformation from symmetrical to asymmetrical interfaces in the annealing process in Al/Zr (Al(1%wtSi)/Zr and Al(Pure)/Zr) systems were also presented.

8777-51, Session 14

Single-shot pulse duration measurements at free-electron lasers based on transient plasma reflectivity change

Robert Riedel, Univ. Hamburg (Germany) and Helmholtz-Institut Jena (Germany); A. A. Shemmary, Deutsches Elektronen-Synchrotron (Germany); M. Gensch, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); T. Golz, Marion Harmand, N. Medvedev, M. J. Prandolini, Deutsches Elektronen-Synchrotron (Germany); Klaus Sokolowski-Tinten, Univ. Duisburg-Essen (Germany); Sven Toleikis, U. Wegner, Beata Ziaja-Motyka, Nicola Stojanovic, Franz Tavella, Deutsches Elektronen-Synchrotron (Germany)

A single-shot temporal diagnostic tool is presented that allows the determination of the free-electron laser pulse duration and the relative arrival time with respect to an external pump-probe laser pulse. The measurements are based on optical cross-correlation in a spatio-temporal decoding setup. The irradiation of a solid dielectric target with an XUV pulse causes photoionization and leads to a high density of energetic electrons within the conduction band. With an ultrashort near-infrared laser pulse the temporally varying transmission of this plasma is probed. Measurements were performed at the FLASH free-electron laser at two distinct wavelengths on fused silica targets, yielding (184±14) fs pulses at 41.5 nm and (21±17) fs at 5.5 nm. The method can be used as an online diagnostic tool for pump-probe experiments when thin silicon nitride membranes are used as targets. Our results are supported by detailed theoretical investigations.

8777-53, Session 14

EUV optics in photoionization experiments *(Invited Paper)*

Andrzej S. Bartnik, Przemyslaw W. Wachulak, Henryk Fiedorowicz, Tomasz Fok, Roman Jarocki, Jerzy Kostecki, Anna Szczurek, Miroslaw Szczurek, Military Univ. of Technology (Poland)

Ionization of a gaseous medium can be obtained by an electrical discharge or intense laser pulse irradiation. In both cases the electron collisional ionization is a dominating mechanism leading to plasma creation. In both cases electrons are accelerated by an electric field and some threshold must be exceeded to initialize the discharge or a laser spark. Quite different possibility ofers irradiation with X-rays or extreme ultraviolet (EUV). In this case a single photon carries enough energy to ionize any atom or molecule. Thus ionization is possible even with low intensity radiation beams. Some photoionization experiments were performed on high power laser or Z-pinch facilities for laboratory simulation of astrophysical plasmas [1,2].

In this work different gases were irradiated with a focused EUV beam from one of two laser-plasma sources employing Nd:YAG laser systems of different parameters. First of them was a 10-Hz laser-plasma EUV source, based on a double-stream gas-puff target, irradiated with the 3-ns/0.8J laser pulse. EUV radiation in this case 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. The second source was based on a 10 ns/10 J/10 Hz laser system. In this case EUV radiation was focused using a gold-plated grazing incidence multifoil collector in the wavelength range ? = 5 ÷ 70 nm. The most intense emission was in the 5 ÷ 15 nm spectral region. Radiation power density in both cases was comparable.

Different gases were injected into the interaction region, perpendicularly to an optical axis of the irradiation system, using an additional gas puff valve. Irradiation of the gases resulted in ionization and excitation of atoms and molecules. Spectra in EUV/VUV range were measured using a grazing incidence, flat-field spectrometer (McPherson Model 251), equipped with a 450 lines/mm toroidal grating. In all cases the most intense emission lines were assigned to singly charged ions. The other emission lines belong to neutral or doubly ionized atoms. The spectra were excited in low density gases of the order of 1% atmospheric density. For higher densities close to 10% of atmospheric density, only He and Ne spectra could be obtained. In case of Ar, O2 and N2 absorption in a cold gas surrounding the interaction region strongly attenuates the radiation. Emission spectra obtained in case of both laser-plasma sources were compared.

[1] R. C. Mancini, J. E. Bailey, J. F. Hawley, T. Kallman, M. Witthoeft, S. J. Rose, H. Takabe, Phys. Plasmas 16 (2009) 041001

[2] S. Fujioka, H. Takabe, N. Yamamoto, D. Salzmann, F.Wang, H. Nishimura, Y. Li, Q. Dong, S. Wang, Y. Zhang, Y. Rhee, Y. Lee, J. Han, M. Tanabe, T. Fujiwara, Y. Nakabayashi, G. Zhao, J. Zhang, K. Mima, Nature Phys. 5 (2009) 821-825

8777-54, Session 14

On the problem of measurements of polarization of the FEL radiation

Sergei V. Bobashev, Ioffe Physico-Technical Institute (Russian Federation); A. A. Markova, St. Petersburg State Polytechnical Univ. (Russian Federation)

The degree of polarization is an important characteristic of radiation. Determination of the polarization degree with a high accuracy in vacuum ultraviolet(VUV) and soft-X-ray (SXR) spectral ranges is a complicated problem.

In [1,2] a new method for polarization measurement have been announced. The method is supposed to be used for vacuum ultraviolet synchrotron radiation polarization (linear, circular and elliptical). The method is based on frequency transformation of VUV or SXR radiation into the low energy region of the spectrum by means of exciting the fluorescence in a suitable manner, on the measurement of polarization parameters of the fluorescence light, and finally, on the calculation of polarization parameters of investigated radiation using the known transformation formulas [3]. A new method has been demonstrated to be experimental feasible [4] .Later several modifications of this technique have been proposed. In [5] a technique of recoding dichroism in absorption a probe-beam by exited atomic and molecular gas was proposed. The possibility for determination of the degree of polarization of synchrotron radiation by measuring linear dichroism in stepwise ionization of an autoionizaton state of an atom with a known total momentum have been considered in [6]. In papers mentioned main concern was the accuracy of resulting data of polarization parameters that depends greatly on intensity of radiation to be measured. Intensive radiation from Free Electron Lasers (FEL) will make application of new methods for express determination of polarization as a practical technique.

[1]S.V. Bobashev and O.S. Vasyutinskii, Sov. Thech, Phys. Lett, 11, 599, (1985)

[2] S.V. Bobashev and O.S. Vasyutinskii, Rev. Sci. Instr. 63(1), 1509,

(1992)

[3]V.Yu. Bakman, S. V. Bobashev, O. S. Vasyutinskii, Tech. Phys., 44, 1103-1110, (1999).

[4]C.J.Latimer, M.A.MacDonald, P.Finetti, Jornal of Electron Spectroscopy and Related Phenomena 101-103, (1999},875-878.

[5]V.Yu .Bakman, S. V. Bobashev, O. S. Vasyutinskii, Tech. Phys. Lett., 20, 14-18, (1994).

[6] A.Yu.Elizarov, Opt. Spectrosc.,v.88, (5), 762-764, (2000).

8777-55, Session 15

A novel monochromator for ultrashort soft X-ray pulses

Maria Brzhezinskaya, Alexander Firsov, Karsten Holldack, Torsten Kachel, Rolf Mitzner, Niko Pontius, Christian Stamm, Jan-Simon Schmidt, Alexander Foehlisch, Alexei Erko, Helmholtz-Zentrum Berlin (Germany)

Sub-ps time-resolved experiments in the soft x-ray range require beamlines equipped with reflection gratings or reflecting diffractive focusing elements that preserve, at best, the temporal-, transverse- and flux properties of the beam. In case of storage ring based ultrafast sources (slicing) and HHG-sources, where the average flux is rather low, a high transmissive optics that preserves the pulse length (~100 fs or lower) is mandatory.

Reflection zone plates (RZP), which consist of elliptical zone plates fabricated on a total external reflection mirror surface, can be effectively used to produce a monochromatic x-ray beam and to focus it at photon energies below 1400 eV. However, as RZPs are highly chromatic, they can be designed only for one specific photon energy. We alleviate this problem by using a novel approach: a Reflection Zone Plate Array (RZPA).

Here, we report about successful implementation of novel monochromator based on RZPAs for experiments with 100 fs time resolution at the upgraded Femtoslicing facility at BESSY-II. Aiming at minimum losses in x-ray flux at reasonable resolution, we fabricated and used an RZPA as a single optical element for diffraction and focusing. Nine Fresnel lenses, designed for the energies of 410 eV, 543 eV, 644 eV, 713 eV, 786 eV, 861 eV, 1221 eV and 1333 eV which correspond to the absorption edges of N-K, O-K, Mn-L, Fe-L, Co-L, Ni-L, Gd-M and Dy-M, were fabricated on the same substrate with a diameter of 100 mm. At reasonable resolution E/?E=500 (2000 for Fe) all edges of other elements in that range (~400-1400 eV) are covered, too. Results from commissioning and first feedback from user operation that started in November 2012 will be presented.

This work was financially supported by the BMBF project “Next generation instrumentation for ultrafast X-ray science at accelerator-driven photon sources” (project no. 05K12CB4) and a Marie Curie FP7-Reintegration-Grants within the 7th European Community Framework Program (project no. PCIG10-GA-2011-297905) as well as the internal strategic investment fund of the HZB.

8777-56, Session 15

4H-SiC and novel SI GaAs-based M-S-M radiation hard photodetectors applicable in UV, EUV and soft X-ray detection: design, technology and performance testing

Frantisek Dubecky, Institute of Electrical Engineering, Slovak Academy of Sciences (Slovakia); Jaroslav Kovár, Institute of Electronics and Photonics, Slovak University of Technology (Slovakia); Bohumír Zarko, Institute of Electrical Engineering, Slovak Academy of Sciences (Slovakia); Jirí Osvald, Pavel Hubík, Dobroslav Kindl, Institute of Physics, v.v.i., Academy of Sciences of the Czech Republic (Czech Republic); Gabriel Vanko, Pavol Bohácek, Institute of Electrical Engineering, Slovak Academy of Sciences (Slovakia); Andrea Sagátová-Perdochová, Vladimír Necas, Institue of Nuclear and Physical Engineering, Slovak University of Technology (Slovakia); Mária Sekácová, Institute of Electrical Engineering, Slovak Academy of Sciences (Slovakia)

4H-SiC detectors applicable in detection of UV and EUV photon ranges [1] were introduced. Their high radiation resistance to damage by neutrons and gamma rays was recently demonstrated [2]. Serious attractive feature of the detectors present high quantum efficiency and blindness in the visible spectral range. Hence no usage of a special filter, as e.g. in case of Si detectors, is necessary. GaAs-based M-S-M detectors present another potential candidate with improved resistance against radiation damage. Their detection ability in the far UV spectral region was already previously demonstrated [3], however their disadvantage due to sensitivity in the visible range retain.

Present work reports on results in development of 4H-SiC and semi-insulating (SI) GaAs large area (1 – 9 mm2) surface barrier detectors. 4H-SiC detectors are based on high purity liquid phase epitaxy layer with barrier contact formed by semitransparent Ni or Pt. SI GaAs detectors are based on bulk undoped material using novel electrode metallization giving an improved sensitivity in UV and soft X-ray range ranges. The detectors use semitransparent low work function metal contact (Mg, Gd) presenting new electronic properties of the M-SI GaAs junction [4]. Planar as well as sandwich contact configurations are developed for both materials.

Electrical characteristics of the diodes, photocurrent (PC) measurements and pulse height spectra of low energy X-rays using 241Am source are presented. Improvement of detectors resistance to radiation and neutron fluency is demonstrated. Problems with design and application of related ultra-low noise electronics are introduced and discussed.

[1] X. Xin, F. Yan, T.W. Koeth, C. Joseph, J. Hu, J. Wu, and J.H. Zhao, Demonstration of 4H-SiC visible-blind EUV and UV detector with large detection area, El. Lett. 41 1192 (2005)

[2] F. Dubecky, et al., Characterization of epitaxial 4H-SiC for photon detectors, J. Instrument. 7 P09005 (2012)

[3] M. Caria, L. Barberini, S. Cadeddu, A. Giannattasio, A. Rusani, A. Sesselego, A. Lai, S. D´Auria, and F. Dubecky, Gallium arsenide photodetectors for imaging in the far ultraviolet region, Appl. Phys. Lett. 81 1506 (2002)

[4] F. Dubecky, M. Dubecky, P. Hubík, D. Kindl, E. Gombia, M. Baldini, and V. Necas, Unexpected Current Lowering by a Low Work-Function Metal

Conference 8778: Advances in X-ray Free-Electron Lasers II: Instrumentation

Wednesday - Thursday 17–18 April 2013

Part of Proceedings of SPIE Vol. 8778 Advances in X-ray Free-Electron Lasers II: Instrumentation

8778-1, Session 1

The FERMI@ELETTRA free-electron laser: a coherent laser source in the VUV/soft X-ray spectral range *(Invited Paper)*

Giovanni De Ninno, Univ. of Nova Gorica (Italy)

FERMI@Elettra is the first VUV/soft X-ray seeded free-electron laser in the world open to user experiment. Presently, it has unique performance in terms of stability, (longitudinal and transverse) coherence and variable polarization. FERMI's layout relies on a single (FEL-1) and a double (FEL-2) harmonic generation cascade. FEL-1 generates light in the spectral range between 100 nm and 20 nm, and is now fully commissioned. FEL-2 is presently under commissioning, and aims at generating light in the range between 20 nm and 4 nm. During the talk, we will present the concept on which FERMI is based, as well as the first obtained results and future planned developments.

8778-2, Session 1

Harmonic lasing in X-ray FELs *(Invited Paper)*

Evgeny Schneidmiller, Mikhail V. Yurkov, Deutsches Elektronen-Synchrotron (Germany)

Contrary to nonlinear harmonic generation, harmonic lasing in a high-gain FEL can provide much more intense, stable,and narrow-band FEL beam which is easier to handle if the fundamental is suppressed. We perform a parametrization of the solution of the eigenvalue equation for lasing at odd harmonics, and present an explicit expression for FEL gain length, taking into account all essential effects. We propose and discuss methods for suppression of the fundamental. We also suggest a combined use of harmonic lasing and lasing at the retuned fundamental wavelength in order to reduce bandwidth and to increase brilliance of X-ray beam at saturation. We discover that in a part of the parameter space, corresponding to the operating range of soft X-ray beamlines of X-ray FEL facilities (like SASE3 beamline of the European XFEL), harmonics can grow faster than the fundamental. We find out that harmonic lasing is much more robust than usually thought, and can be widely used in the existing or planned X-ray FEL facilities. LCLS after a minor modification can lase at the 3rd harmonic up to the photon energy of 25-30 keV providing multi-gigawatt power level. At the European XFEL the harmonic lasing would allow to extend operating range ultimately up to 100 keV. Harmonic lasing can be an attractive option for compact X-ray FELs (driven by electron beams with a relatively low energy), allowing the use of the standard undulator technology instead of small-gap in-vacuum devices. We discuss a possible experiment on harmonic lasing at LCLS.

8778-3, Session 1

Coherent THz Radiation from linacs and 4th Generation X-ray Light sources

Nikola Stojanovic, DESY (Germany)

The last decade witnessed the rise of new type of accelerator light sources based on linear accelerators. Like synchrotron sources, these large-scale facilities have the appeal of their broad spectral range (from the THz to hard X-rays) as well as their tunability. However, their advantage over synchrotrons lays in the ability to generate ultra-short pulses with peak intensities many orders of magnitude higher.

Particularly in in THz range, the ability of 4th generation sources to generate pulses with electric field strength in the few 10 to 100 MV/m range opened the door to a number of exciting experiments especially in the field of non-linear THz spectroscopy and THz control experiments. A variety of different source concepts allows shaping the THz pulses from single cycle/broad band pulses to many-cycle/narrow-bandwidth pulses and polarizations ranging from radial to linear. The main advantage of accelerator-based THz originates from the fact that the THz generation process does not take place in a medium but in the accelerator vacuum, and therefore that the THz pulse energy can be scaled up much easier than in case of the table top sources available today. In addition, it has been demonstrated recently that coherent THz radiation can be generated along femtosecond X-ray pulses in 4th Generation X-ray Light sources such as FLASH [1, 2, 3] and LCLS [4]. This opens up the exciting opportunities for naturally synchronized THz pump X-ray probe experiments on few femtosecond time scales [1, 2, 4]. Here is given an overview over different THz facility projects will and experimental opportunities and challenges are discussed with the example of recent pilot experiments.

[1] M. Gensch et. al., New infrared undulator beamline at FLASH, Infrared Phys. Technol. 51 (2008), 423.

[2] U. Fruehling et. al., Single-Shot THz-field-driven X-ray streak camera, Nat. Photon. 3 (2009), 523.

[3] F. Tavella, N. Stojanovic, G. Geloni, M. Gensch, Few-Femtosecond timing at Fourth-Generation X-ray Light sources, Nat. Photon. 5 (2011), 162.

[4] D. Daranciang et. al., Single-cycle terahertz pulses with > 0.2 V/angstrom field amplitudes via coherent transition radiation, Appl. Phys. Lett. 99 (2011), 141117.

8778-4, Session 1

Two colors SASE FEL experiment at SPARC_LAB

G. Gatti, Istituto Nazionale di Fisica Nucleare (Italy)

We discuss in this presentation a simple method to generate a tunable two wavelengths FEL pulse with variable time separation based on the comb technique recently developed at SPARC_LAB. The electron beam, constituted by two bunches with different energy, can be extracted from the accelerating section operating in the velocity bunching mode when they are separated in energy, so that each of them is characterized by a different value of the Lorentz factor. When correctly matched to the FEL undulator, they can emit two separate spectral lines, according to the FEL resonance condition. In this way a double FEL pulses can be obtained with possible applications in pump and probe experiments.

8778-5, Session 2

Magnetic systems studied with linear and circular polarized FEL radiation *(Invited Paper)*

Gerhard Gruebel, Deutsches Elektronen-Synchrotron (Germany)

Understanding ultrafast magnetization dynamics on the nano-scale is a forefront problem in modern magnetism research with direct impact on the quest for faster and smaller storage devices. Probing the magnetization element-specifically and on the nanometer length-scale is a pre-requisite when probing technologically relevant material systems with complex composition.

X-ray free electron laser (FEL) sources with their unique properties delivering ultrashort and super intense soft X-ray pulses allow for the first time to address magnetization dynamics on the relevant length scale.

We present recent results obtained on multi-domain Co/Pt magnetic multilayer samples with perpendicular magnetic anisotropy. As a probe we use small angle X-ray scattering from the magnetic domains which, via X-ray magnetic circular dichroism at the Co M-edge, allows us to simultaneously obtain information on the magnitude of the local magnetization and the characteristic length scale of the domains. The FEL source FLASH at DESY (Hamburg) was tuned to deliver soft

X-ray pulses with a length of about 80 fs and a wavelength of 20.8 nm corresponding to the Co M-edge.

Single-pulse resonant magnetic scattering using a soft x-ray free-electron laser, C. Gutt et al., Phys. Rev. B 81, 100401(R), (2010)

Ultrafast Optical Demagnetization manipulates Nanoscale Spin Structure in Domain Walls, B. Pfau et al., Nature Communication 3, Article number: 11; doi:10.1038/ncomms2108

8778-6, Session 2

Four wave mixing using coherent FEL radiation *(Invited Paper)*

Filippo Bencivenga, Synchrotron Trieste S.C.p.A. (Italy); Lorenzo Raimondi, Cristian Svetina, Sincrotrone Trieste S.C.p.A. (Italy); Claudio Masciovecchio, Elettra (Italy)

The development of Free Electron Laser sources is opening up the possibility to probe dynamics at the femtosecond-nanometer time-length scales. A remarkable step forward towards this goal would be achieved by extending the Four Wave Mixing (FWM) approach at VUV/soft x-ray wavelengths. FWM-based techniques allow a coherent control in both the stimulating and probing processes of photon-induced excitations. We propose to exploit the FERMI@Elettra seeded Free Electron Laser (FEL) source to put on practice the VUV/soft x-ray FWM approach, yet theoretically conceived one decade ago. Moreover, the exploitation of VUV/soft x-ray wavelengths allows adding site-sensitivity to FWM methods by exploiting core resonances of selected elements in the sample.

8778-7, Session 2

The impact of pulse duration on multiphoton ionization in the soft X-ray regime

Mathias Richter, Physikalisch-Technische Bundesanstalt (Germany); Andrey A. Sorokin, Kai Tiedtke, Deutsches Elektronen-Synchrotron (Germany)

At the soft X-ray free electron laser FLASH, multiphoton ionization of free atoms has been studied by ion time-of-flight spectroscopy. Depending on the multiphoton mechanism, the ionization processes are influenced in different ways by the FEL pulse duration. This feature has been used, e.g., to measure the pulse duration of FLASH in the femtosecond regime by nonlinear autocorrelation. In the present contripution, the impact of pulse duration on multiphoton ionization will be discussed with emphasis to the distinction between sequential and non-sequential processes and strong-field effects as well.

8778-8, Session 2

Coherence measurement in the water window and time-resolved single-shot diffraction of lipid membrane with fs FEL-pulses

Dong-Du Mai, Tim Salditt, University Göttingen (Germany)

Phospholipid membranes are intensively studied as simple model systems to understand the fundamental structural and physical aspects of their much more complex biological counterparts. The lateral structure of membranes including both height and compositional fluctuations remains an important experimental challenge of present-day biophysics.

At FLASH, we carried out optical pump/X-ray probe experiments / PP/ on phospholipid /DOPC/ multilamellar membranes, using a Ti:Sa fs-laser for excitation while probing the system with single as well as with successive FEL pulses. These single shot coherent diffraction patterns of the first diffuse Bragg sheet were recorded with the 3rd FEL harmonic at 2.66 nm. The signal is speckled due to the coherent illumination, and corresponds to the mulitlamellar periodicity of 5 nm (inter bilayer distance), which are probably the smallest structures resolved at FLASH so far. The intensity histogram of the speckle pattern reveals an average number of transverse modes of _M = 2.7 of the 3rd harmonic, which corresponds to a spatial coherence of 37%. By varying the excitation power and impact area of both laser and FLASH pulse, the structural dynamics of the DOPC multilayers on the ps-time scale after excitation by strong out-of-equilibrium fields can be probed. Fitted peak position and width (FWHM) are evaluated as a function of time delay for several parameters (illumination, focus vs. defocus, averaging). The resulting curves depend on the precise averaging schemes and are presently still subject to ongoing analysis. The peak parameters reflect the DOPC bilayer thickness and ordering after the optical excitation.

In addition we found that during the measurement campaign the relative wavelength fluctuations of the third harmonic exhibited a standard variation of 1.24%, corresponding to an absolute value of 0.033 nm. This agrees very well with bandwidth measurements of the fundamental, performed before and after the present experiment, which gave an (average) bandwidth of 1.1% (standard variation), noted as 2.5% FWHM in the FLASH logbook. Hence as expected, the bandwidth of the first and 3rd harmonic are identical within experimental errors. These fluctuations can impose a problem, e.g. for pump-probe experiments where only small changes of observables are expected after excitation, which can easily be masked by pulse-to-pulse fluctuations in photon energy.

8778-9, Session 3

Adaptive/bimorph mirror optics for FELs *(Invited Paper)*

Riccardo Signorato, Bruker ASC GmbH (Germany)

The beam transport system of the European XFEL is currently designed including adaptive piezoelectric bimorph technology to control the overall and local shape of the distribution/offset mirrors for the 3 beamlines, SASE1, SASE2 and SASE3. In order to preserve the quality of the XFEL beam wavefront, an exceptionally stringent requirement on shape error of the mirrors is set at the unprecedented level of better than 2nm PV over at least 700mm optical length, with the focusing curvature continuously tunable between an ideal flat and 50km spherical radius. To fulfill these extreme requirements under the expected heat load of up to 100W, a bimorph mirror based on a novel concept with four rows of PZT actuators attached on the four corners of the silicon substrate, and including provisions for cooling has been carefully designed. Using the finite element tool ANSYS, static thermal and mechanical performance of this innovative bimorph mirror were simulated in detail. A prototype is being manufactured.

8778-10, Session 3

Recent development of thin diamond crystals for X-ray FEL beam-sharing

Yiping Feng, SLAC National Accelerator Lab. (United States)

The recent scientific success of the X-ray FEL's has prompted great interests from users in a wide range of scientific disciplines including physics, chemistry, structural biology, and material science, and has created very high demand on FEL beam access. Due to the serial nature of the FEL operation, various beam-sharing techniques have been investigated to increase FEL capacities. Here we report the recent development in using thin diamond crystals for spectrally split the SASE FEL beam to allow simultaneous operation of multiple instruments and experimental findings in beam stability, impact of the crystal on the FEL transverse coherence and wavefront, and efficiency.

8778-11, Session 3

Development of active gratings for the spectral selection of ultrafast pulses

Stefano Bonora, Fabio Frassetto, Giovanna Brusatin, Gioia Della Giustina, Univ. degli Studi di Padova (Italy); Salvatore Stagira, Politecnico di Milano (Italy); Caterina Vozzi, Carlo Zanchetta, Luca Poletto, Univ. degli Studi di Padova (Italy)

We present the design and characterization of active deformable gratings to be used for the realization of extreme-ultraviolet monochromators. The device consists of a bimorph deformable mirror on the top of which a diffraction grating with laminar profile is realized by UV lithography. The curvature radius of the grating substrate can be varied changing the voltage applied to an underlying piezo-actuator. The advantage of this technology is to provide gratings with high optical quality, robust, compatible with any coating deposition and realized with only vacuum-compatible materials. We present the characterization of some of the prototypes in the extreme ultraviolet and in the visible, showing that the active grating can optimize the beam focusing through its rotation and deformation. Two equal active gratings have been mounted in a compensated configuration to realize a grazing-incidence double-grating monochromator for the spectral selection of ultrashort pulses and the simultaneous compensation of the pulse front-tilt given by the diffraction. The wavelength scanning is performed by the first grating through rotation. The radiation is focused on the intermediate plane, where a slit carries out the spectral selection. Finally, the second grating compensates for the pulse front-tilt given by the first one. The spectral focusing of both gratings is maintained at the different wavelengths through the variation of the radii of curvature. The instrument has been tested with a Ti:Sa laser operated at 800 nm. We have been able to demonstrate that the double-grating configuration with active gratings compensates for the pulse front-tilt, that is reduced from 1 ps at the intermediate plane to 100 fs at the output. The final value is limited by the group delay dispersion of the monochromator within the 10-nm bandwidth of the laser. Active gratings may be considered as a cheaper and more flexible alternative to standard gratings for the realization of extreme-ultraviolet monochromators for ultrafast pulses, such as free-electron lasers and high-order laser harmonics.

8778-12, Session 3

Fabrication and characterization of B4C coatings for advanced research light sources

Michael Störmer, Helmholtz-Zentrum Geesthacht (Germany); Igor V. Kozhevnikov, A.V. Shubnikov Institute of Crystallography (Russian Federation); Frank Siewert, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Harald Sinn, Liubov Samylova, European XFEL GmbH (Germany); Jérôme Gaudin, European XFEL GmbH (France)

X-ray optical elements are required for beam transport at the upcoming free-electron lasers and synchrotron sources. An x-ray mirror is a combination of a substrate and a coating. The demand for large mirrors with single layers consisting of light or heavy elements has increased during the last decade, since surface finishing technology is able to process longer mirror lengths on the sub-nanometer level. Additionally, thin-film fabrication is able to deposit some tens of nanometers of a suitable single layer material. After deposition, the mirror should provide excellent x-ray optical properties with respect to thickness errors, roughness values and slope errors, then the mirror will transport the x-ray beam with high reflectivity, high beam flux and preserved wavefront to the experimental stations.

Amorphous layers of boron carbide with a thickness in the range of 30 nm to 50 nm were fabricated using the HZG sputtering facility, which is able to cover areas up to 1500 mm by 120 mm in one step using rectangular B4C sputtering targets. The available deposition area is quite suitable to the specified mirror dimensions of upcoming advanced research light sources. These coatings were investigated by means of x-ray reflectometry (XRR), stylus profilometry and interference microscopy. The achieved results are discussed according to thickness uniformity, density, roughness, thermal stability and elemental composition of the B4C layers.

The variation of layer thickness in the tangential and sagittal directions was investigated in order to estimate the achieved level of uniformity over the whole deposition area. A waisted mask was used during deposition to improve the thickness uniformity especially to prevent a convex film shape in the sagittal direction. Furthermore, the inclination of the substrates was varied to change the layer uniformity and to optimize the position of the mirror during deposition. The micro-roughnesses of the mirrors were studied on different substrates before and after deposition of B4C. Furthermore, the thermal stability of the B4C layers was investigated.

8778-13, Session 3

Numerical study of Li2O-based multilayer optics for water-window wavelength radiation

Rolf A. Loch, FOM Institute DIFFER (Netherlands); Ryszard Sobierajski, Institute of Physics (Poland); Jeroen Bosgra, FOM Institute DIFFER (Netherlands); Eric Louis, Fred Bijkerk, FOM Institute DIFFER (Netherlands) and Univ. Twente (Netherlands)

We have theoretically investigated Li2O-based multilayer optics for the water-window range in detail on reflectivity, interface width, damage threshold and spectral bandwidth. The results are compared with Cr/Sc multilayers.

Li2O-based multilayers are promising optics for high reflectivity in the full water-window range, as opposed to Cr/Sc multilayer systems, especially at larger angles of incidence. With comparable interface width as Cr/Sc the reflectivity of Co/Li2O would be more than 30% across the full water-window. At normal incidence Ni/Li2O shows a higher reflectivity at the highest photon energies in the water-window. If the use of oxides in both layer materials would reduce intermixing and hence form sharper interfaces, the NiO/Li2O system could prove to be a better multilayer for normal incidence applications. At larger angles of incidence, the relative difference between the different Li2O-based multilayers becomes smaller.

In addition, Li2O-based multilayers have higher single-shot damage thresholds than Cr/Sc making them more suitable for use at high-intensity radiation sources. CoO/Li2O has the highest damage threshold, but a low reflectivity. For this reason, NiO/Li2O would be the best compromise between damage threshold and reflectivity. At normal incidence the damage thresholds in the water-window are between 200 and 700 mJ/cm2, and at 60o from normal incidence between 100 and 460 mJ/cm2. Also for the damage thresholds, the difference between the several Li2O-based multilayers becomes smaller at larger angles of incidence.

The spectral resolution of these Li2O-based multilayers is also higher, which is important for use as monochromators. Also for this purpose NiO/Li2O performs best. At normal incidence, assuming zero interface roughness, the photon energy dependent resolution E/deltaE increases from 280 to 600 for energies close to the oxygen absorption edge. The resolution further increases when taking into account non-zero interface widths. The resolution decreases for larger angles of incidence, but still peaks above 300 close to the oxygen edge at 60 degrees from normal incidence.

To finalize, Co/Li2O and NiO/Li2O are promising multilayer optics to be investigated experimentally. The growth of the layers and the interface width due to intermixing and roughness would give more insight in the usefulness of these multilayers for real applications like SXR microscopy or spectroscopy with laboratory sized sources or high brightness FELs.

8778-14, Session 3

Nanofocusing and single shot wavefront diagnosis of SACLA

Kazuto Yamauchi, Osaka Univ. (Japan); Makina Yabashi, RIKEN (Japan); Hidekazu Mimura, The Univ. of Tokyo (Japan); Hirokatsu Yumoto, Takahisa Koyama, Kensuke Tono, Tadashi Togashi, Japan Synchrotron Radiation Research Institute (Japan); Yuichi Inubushi, Takashiro Sato, Tetsuji Katayama, RIKEN (Japan); Satoshi Matsuyama, Jangwoo Kim, Ryosuke Fukui, Y. Sano, Osaka Univ. (Japan); Wataru Yashiro, The Univ. of Tokyo (Japan); Takashi Ohmori, RIKEN (Japan); Shunji Goto, Haruhiko Ohashi, Japan Synchrotron Radiation Research Institute (Japan); Atsushi Momose, Tohoku Univ. (Japan); Tetsuya Ishikawa, RIKEN (Japan)

We developed 1?m and 50nm focusing optics for SACLA by using total reflection Kirkpatrick-Baez (KB) mirrors. In the 50nm optics, we employed a two-step focusing by using two KB mirrors to realize large enough numerical aperture with long enough working distance. The

wavefront error was measured by a single shot grating interferometry. We found the wavefront error of the focused beam originates in the shape error of the downstream KB mirrors and is smaller than ?/4, which means to be under diffraction-limited condition. The peak power at the focal spot was calculated to be 1020W/cm2 by supposing the pulse duration of 10fs, which is estimated by energy spectra of SACLA beam.

We will show the optics, measured beam profiles, and wavefront shapes of the focused beam. In addition, we will show some results of ablation threshold tests for the mirror design of the next-generation focusing mirror optics.

[1] Yumoto et al., Nature Photonics (2012)

8778-15, Session 3

Full characterization of a focused wave field with sub 100 nm resolution

Robert Hoppe, Technische Univ. Dresden (Germany)

Many experiments require a highly focused hard x-ray beam. Different types of x-ray optics like refractive lenses, diffractive zone plates, reflection mirrors and waveguides are regularly used to generate such beams. These optics vary in beam shape, intensity distribution and phasing. A detailed knowledge of the illumination is essential to evaluate most of the experiments. Up to recently only available technique to analyze the wave front at FELs was the imprint technique, which is based on the radiations damage to a thin layer of matter. From this data a rough estimate of the shape of a single shot and the relative intensity between several shots can be extracted. The intensity distribution and the phasing stays completely out of reach by that method.

During the last decade a new technique has been developed to reconstruct the full information about the utilized wave field and of the object. The so-called ptychography solves the phasing problem of coherent far-field imaging. Thereby the object is raster scanned with an overlap between adjacent illumination points. At each raster point a far-field diffraction pattern is acquired. An iterative phasing algorithm reconstructs the complex illumination and object functions from the set of far-field patterns. The complex object function describes the absorption and refraction strength of the sample. In addition the illumination is reconstructed in amplitude and phase of a complex wave field. With this information about the illumination the radiation field along the optical axis can be calculated.

We adapted the technique to the constraints,that are set by the high intensities of a hard x-ray FEL and undertook an experiment at SLAC, USA to characterize a focused x-ray beam at 8.2 keV with better spatial resolution than 70 nm.

8778-16, Session 3

Measurement of wavefront and Wigner distribution function for optics alignment and full beam characterization of FELs

Tobias Mey, Bernd Schäfer, Laser-Lab. Göttingen e.V. (Germany); Bernhard Flöter, Volkswagen AG Wolfsburg (Germany); Klaus Mann, Laser-Lab. Göttingen e.V. (Germany); Barbara Keitel, Marion Kuhlmann, Elke C. Plönjes-Palm, Kai Tiedtke, Deutsches Elektronen-Synchrotron (Germany)

Free-Electron-Lasers deliver EUV and soft x-ray pulses with the highest brilliance available and high spatial coherence. Users of such facilities have high demands on phase and coherence properties of the beam, for instance when working with coherent diffractive imaging (CDI).

Experimentally, we are recovering the phase distribution with a EUV Hartmann wavefront sensor. This allows for online adjustment of focusing optics such as ellipsoidal or Kirkpatrick-Baez mirrors minimizing the aberrations in the focused beam.

To gain highly resolved spatial coherence information, we have performed a caustic scan at beamline BL2 of the free-electron laser FLASH using the ellipsoidal focusing mirror and a movable EUV sensitized CCD detector. This measurement allows for retrieving the Wigner distribution function, being the two-dimensional Fourier transform of the mutual intensity of the beam. Computing the reconstruction on a four-dimensional grid, this yields the entire Wigner distribution which describes the beam propagation completely. Hence, we are able to provide comprehensive information about spatial coherence properties of the FLASH beam including the global degree of coherence. Additionally, we derive the beam propagation parameters such as Rayleigh length, waist diameter and M?.

8778-17, Session 3

Two-dimensional coherence measurements of FEL radiation: the heterodyne speckle approach

Matteo D Alaimo, Michele Manfredda, Marco A C Potenza, Marzio Giglio, Univ. degli Studi di Milano (Italy)

We developed a heterodyne speckle method for measuring the transverse coherence of synchrotron and FEL radiation. The technique needs a very essential setup, composed only by a water suspension of commercial colloidal particles and a CCD camera. The modulus of the Complex Coherence Factor is retrieved from the Fourier analysis of the interference pattern generated by the stochastic superposition of the almost spherical waves scattered by the particles and the transmitted beam (heterodyne speckles). The method has been previously developed and tested to be effective with synchrotron radiation (l = 0.1nm) [*,**] (ID02 and ID06 at ESRF, Grenoble). We recently applied it for the characterization of a FEL source in SASE regime in the optical region (400nm) at SPARC (LNF, Frascati - Italy). It turned out that the coherence length is comparable with the beam size and only slight variations of the coherence properties have been observed after the 5th undulator section. This approach offers a number of advantages. First, it does not require the engineering of ad-hoc devices and it is easily transposable to a wide range of wavelengths. Second, it provides a two-dimensional map of the transverse coherence without any a-priori assumption about its functional form and with no use of reconstruction algorithms. Third, it is capable of one-shot characterizations and is thus suitable for time-resolved measures and live diagnostics on photon beams.

* M.D. Alaimo, M.A.C. Potenza, M. Manfredda, G. Geloni, M. Sztucki, T. Narayanan & M. Giglio, Phys. Rev. Lett. 103 (2009).

** M. Manfredda et al., in preparation

8778-35, Session PS

Beam characterization of FLASH from beam profile measurement by intensity transport equation and reconstruction of the Wigner distribution function

Bernd Schäfer, Tobias Mey, Klaus Mann, Laser-Lab. Göttingen e.V. (Germany); Barbara Keitel, Elke C. Plönjes-Palm, Marion Kuhlmann, Kai Tiedtke, Deutsches Elektronen-Synchrotron (Germany)

Beam parameters of the free-electron laser FLASH @13.5 nm in two different operation modes were determined from beam profile measurements and subsequent reconstruction of the Wigner distribution function behind the ellipsoidal focusing mirror at beamline BL2. 40 two-dimensional single pulse intensity distributions were recorded at each of 65 axial positions around the waist of the FEL beam with a magnifying EUV sensitized CCD camera. From these beam profile data the Wigner distribution function based on different levels of averaging could be reconstructed by an inverse Radon transform. For separable beams this yields the complete Wigner distribution whereas for beams with zero twist the information is still sufficient for wavefront determination and beam propagation through stigmatic or aligned astigmatic systems. The obtained results are compared to wavefront reconstructions based on the transport of intensity equation. A future setup for Wigner distribution measurement of general beams is discussed.

8778-36, Session PS

Tunable IR/THz source for pump probe experiments at the European XFEL

Mikhail V. Yurkov, Evgeny Schneidmiller, Mikhail Krasilnikov, Frank Stephan, Deutsches Elektronen-Synchrotron (Germany)

We present a concept of an accelerator based source of powerful, coherent IR/THz radiation for pump-probe experiments at the European XFEL. The electron accelerator is similar to that operating at the PITZ facility. It consists of an rf gun and a warm accelerating section (energy up to 30 MeV). The radiation is generated in an APPLE-II type undulator, thus providing polarization control. Radiation with wavelength below 200 micrometers is generated using the mechanism of SASE FEL. Powerful coherent radiation with wavelength above 200 micrometers is generated in the undulator by a tailored (compressed) electron beam. Properties of the radiation are: wavelength range is 10 to 1000 micrometers (30 THz - 0.3 THz), radiation pulse energy is up to a few hundred microjoule, peak power is 10 to 100 MW, spectrum bandwidth is 2 - 3%. Pump-probe experiments involving ultrashort electron pulses can be realized as well. The time structure of the THz source and x-ray FEL are perfectly matched since the THz source is based on the same technology as the injector of the European XFEL. A similar scheme can also be realized at LCLS, SACLA, or SWISS FEL with S-band rf accelerator technology.

8778-37, Session PS

Status of the FLASH II extension to FLASH

E. Plönjes, Bart Fraatz, Deutsches Elektronen-Synchrotron (Germany)

The FLASH II project is a major extension, which will upgrade the soft X-ray free electron laser FLASH at DESY into a multi-beamline FEL user facility. Currently, an additional undulator beamline, FLASH2, is added in a separate tunnel with the option to extend in the future the facility with a third undulator line, FLASH3, also in the new tunnel. The present FLASH linear accelerator will drive both undulator beamlines. FLASH2 will be equipped with variable-gap undulators to be able to deliver two largely independent wavelengths to user endstations at FLASH1 and FLASH2 simultaneously. Civil construction of the new buildings has started in autumn 2011 and will continue in several steps until fall 2013. The design of the new undulator beamline including the extraction from the FLASH linac is mostly finished, and manufacturing of the components is under way. Mounting of the beamline will start in spring 2013, and commissioning with beam is scheduled to start in the second half of 2013.

A new experimental hall will offer space for up to six user endstations, some of which will be installed permanently while other user experiments are brought to the facility only for the beamtimes. The beamline system will be set up to cover a wide wavelength range with at least one beamline capable to deliver the 5th harmonic at 0.8 nm while others will cover the longer wavelengths of 4 - 40 nm and beyond.

8778-38, Session PS

Micro-focusing of soft X-ray pulses by grazing-incidence toroidal mirrors

Luca Poletto, Istituto di Fotonica e Nanotecnologie (Italy); Fabio Frassetto, Institute of Photonics and Nanotechnologies (Italy); Sunilkumar Anumula, Politecnico di Milano - Department of Physics (Italy); Francesca Calegari, Istituto di Fotonica e Nanotecnologie (Italy); Andrea Trabattoni, Mauro Nisoli, Politecnico di Milano (Italy)

We present the design of optical systems for micro-focusing of soft X-ray free-electron-laser (FEL) pulses through grazing-incidence toroidal mirrors. Aim of the configuration is to provide a micro-focused image through a high demagnification of the source (i.e. a demagnification factor higher than 20). The use of toroidal mirrors is presented as an alternative to the use of conventional Cartesian surfaces (i.e. ellipsoidal and paraboloidal). We present the analytical and numerical study of two different configurations. Configuration 1 consists of a pair of mirrors in Z-shaped geometry: the first mirror provides high demagnification (>10) in a stigmatic configuration, the second mirror acts as a relay section with small demagnification (<3) and is designed to minimize the high-order aberrations provided by the first mirror. Configuration 2 consists of three mirrors: the first two mirrors are used to provide high demagnification in a collimator-focusing geometry, i.e. the first mirror acts as the collimator and the second mirror as the condenser. The third mirror acts as a relay section with small demagnification in Z-shaped geometry, similarly to configuration 1. We provide an analytical and numerical study of the optical performance of the configurations and show that the resulting image is stigmatic and almost free from coma aberrations for both configurations, since the coma-type aberration given by the first section, that would be unacceptable for micro-focusing imaging, is compensated by the last mirror. The main advantage of configuration 2 is the availability of a parallel beam in the collimator-condenser section, where the FEL beam may be divided through plane mirrors in two portions that are relatively delayed to provide pump-probe FEL experiments. Some examples will be provided to demonstrate the capability to achieve spot sizes definitely smaller than 10 micrometers. Furthermore, the effects of the residual aberrations given by the toroidal mirrors on the sub-femtosecond pulse duration will be discussed by studying the dispersion of the optical path-lengths. It will be shown that the residual aberrations may alter the temporal structure of the pulse in the range of few hundreds of attoseconds.

8778-39, Session PS

Hartmann wavefront measurements at FLASH

Barbara Keitel, Svea Kreis, Marion Kuhlmann, Elke C. Plönjes-Palm, Kai Tiedtke, Deutsches Elektronen-Synchrotron (Germany); Bernhard Flöter, Klaus Mann, Tobias Mey, Bernd Schäfer, Laser-Lab. Göttingen e.V. (Germany)

We present Hartmann wavefront measurements performed at FLASH in the focused and unfocused beam, employing a compact Hartmann sensor with an improved design developed in collaboration of DESY and the Laser-Laboratorium Göttingen. This detector is adapted to the special beam properties of FLASH in terms of wavelength, pulse energy and coherence (6-30nm, ~15µJ). The Hartmann plate, a 20µm Ni foil with electroformed holes of 75µm diameter, divides the incoming FEL into subrays and illuminates a phosphor coated CCD chip. From lateral deviations in the spot pattern, the wavefront for single pulses is reconstructed using a modal approach. The measured intensity and phase are used to calculate second moment beam parameters such as beam width, divergence, Rayleigh length, waist position, waist size and M^2. A Zernike expansion of the wavefront provides information on the aberrations of the optical system, resolved into single coefficients such as astigmatism or coma. Wavefront and intensity profiles in any plane along the optical axis are accessible via numerical propagation using the Fresnel-Kirchhoff integral.

We performed online wavefront measurements behind the focusing optic of different beamlines at FLASH, which provides information on typical misalignment effects. These measurements allow for online optimizing the different position and angle parameters of the focusing mirror as well as online calculation of the wavefront rms and further beam parameters.

8778-40, Session PS

K-B bendable system optimization at FERMI@Elettra FEL: impact of different spatial wavelengths on the spot-size

Lorenzo Raimondi, Cristian Svetina, Nicola Mahne, Elettra-Sincrotrone Trieste ScpA (Italy); Daniele Cocco, SLAC National Accelerator Laboratory, 2575 Sand Hill Rd, MS-19 Menlo Park, CA 94025 (United States); Flavio Capotondi, Emanuele Pedersoli, Maya Kiskinova, Elettra-Sincrotrone Trieste ScpA (Italy); Barbara Keitel, Guenter Brenner, Elke C. Plönjes-Palm, Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22603 Hamburg, Germany (Germany); Tobias Mey, Klaus Mann, Laser-Lab. Gottingen e.V. (LLG) Hans-Adolf-Krebs-Weg 1, 37077 Gottingen, Germany (Germany); Marco Zangrando, Elettra-Sincrotrone Trieste ScpA (Italy) and CNR – Consiglio Nazionale delle Ricerche Istituto Officina dei Materiali - TASC, S.S. 14 km 163.5 in (Italy)

FERMI@Elettra, the first seeded EUV-SXR free electron laser (FEL) user facility, located at Elettra- Sincrotrone Trieste S.C.p.A., is under advanced commissioning. The Diffraction and Projection Imaging (DiProI) is one of the three beamlines already operative at FERMI@ Elettra. It employs a Kirkpatrick-Baez (K-B) active X-ray optics system in order to focus the FEL beam on the sample inside the endstation. The aim of the present work is to characterize this optical system in order to improve and optimize its performance in terms of spot size, and consequently of fluence. To this end, we performed a measurement campaign with several diagnostic systems, including a wavefront sensor mounted after the DiProI chamber. Online wavefront measurements allow for optimizing the bending acting on the mirrors' curvature and the angle positions (pitch, roll, and incidence angle) of the K-B system. We have also compared the measurement results with the predictions from simula- tions obtained using the WISE code, starting from mirror actual surface metrology characterization. Filtering the Fourier transform of the mirror surface profiles we have analyzed the impact of spatial wavelengths on the Point Spread Function (PSF) degradation. From wavefront measurements we have inferred a focal spot of 10 ?m x 13.5 ?m confirmed by the PMMA ablation and by a knife-edge estimation. The results from simulations with the WISE code are in agreement with the measurements and show, for different energies of the incident beam, the threshold below which the spatial wavelengths of the K-B mirror surfaces start to have no influence on the PSF degradation.

8778-41, Session PS

Parametric beam instability of the electron bunch in a crystal

Aleksandr V Leonov, Andrei Benediktovitch, Belarusian State Univ (Belarus); Dmitriy Ksenzov, Siegen University (Germany); Ilya Feranchuk, Belarusian State Univ (Belarus); Ullrich Pietsch, Siegen University (Germany)

Effect of the parametric beam instability (PBI) of the relativistic electron beam in a crystal was analyzed theoretically in [1]. This effect is analogous to self-amplification of spontaneous emission mechanism for XFEL with an undulator. However in the case of PBI the transversal modulation of the beam is defined by channeling of the electron in a crystal and longitudinal modulation arises because of the parametric X-ray radiation mechanism. It is shown in the present paper that the current density J in the electron bunch typical for XFEL facility is enough for the beam self-modulation within X-ray range if the crystal thickness is larger than the extinction length L > Lext. This process could be used for generation of the coherent X-ray pulse if the time T of the crystal destruction under action of the bunch is less than its passing time L / c. The value T(J) is estimated on the basis of the rate equations for evolution of the atomic scattering factors during the electron bunch propagation through the crystal.

[1] V.G.Baryshevsky and I.D.Feranchuk, Phys. Lett. A 76, (1980) 452.

8778-42, Session PS

Cross-calibration measurements for online wavelength monitoring at FLASH

Markus Braune, Guenter Brenner, Siarhei Dziarzhytski, P. Juranic, Kai Tiedtke, Deutsches Elektronen-Synchrotron (Germany)

Due to the statistically fluctuating output of SASE FELs it is important to monitor the properties of the radiation pulses permanently in order to tune and optimize the machine performance and meet the user requirements. Regarding the wavelength of the at Free electron LASer in Hamburg (FLASH) there are various spectrometers based on dispersive optical elements serving particularly as diagnostic tool for setting up SASE operation. To go towards online monitoring of the spectral distribution, the photon diagnostics group at FLASH established a variable line spacing grating spectrometer (VLS) [1]. This device uses only a small fraction (5 ? 10 %) of the light in the 1st refraction order for the wavelength determination whereas most of the intensity is passed in 0th order to the user experiment. Restrictions are currently the acquisition rate of 10 Hz (single bunch mode capability) and a short wavelength limit at 5.4 nm in the first refraction order.

A different approach is used for the online photoionization spectrometer (OPIS) which was designed recently by the FLASH photon diagnostics group and has been installed in the photon diagnostics section in the FLASH tunnel. The wavelength determination with this device is based on single photoionization processes of gas phase targets [2,3], for which the relevant quantities of the ionization process like binding energies and photoionization cross sections are well known from literature. Typical target gas pressures are in the range of 10?7 hPa which allows a photon transmission to the user experiment of essentially 100 %.

The OPIS device comprises a set of time-of-flight spectrometers for detection of photo-ions and photo-electrons, respectively. Measuring the spectrometer detector signals by means of fast digitizers recording traces of full bunch trains of FLASH it is possible to have a monitor for micro bunch resolved determination of the spectral distribution basically over the complete wavelength range. The advantages of this device make the OPIS a promising complement to the existing optical dispersive spectrometers.

We report on results of most recent cross-calibration measurements involving different spectrometers for wavelength determination at FLASH.

[1] G. Brenner et al., „First results from the online variable line spacing grating spectrometer at FLASH“, NIM A 635, S99-S103 (2011)

[2] P.N. Juranic et al., “Using I-TOF spectrometry to measure photon energies at FELs”, JINST 4, P09011 (2009)

[3] M. Wellhöfer et al., “Photoelectron spectroscopy as a non-invasive method to monitor SASE-FEL spectra”, JINST 3, P02003 (2008)

8778-43, Session PS

Optical afterburner for a SASE FEL

Torsten Golz, Deutsches Elektronen-Synchrotron (Germany); Robert Riedel, Helmholtz-Institut Jena (Germany); A. A. Shemmary, M. Foerst, Franz Tavella, M. Gensch, Evgeny Schneidmiller, Mikhail V. Yurkov, Nicola Stojanovic, Deutsches Elektronen-Synchrotron (Germany)

The radiation produced by a Self-Amplified Spontaneous Emission Free Electron Laser (SASE FEL) leaves a specific energy pattern over the length of the radiating electrons. This pattern, the SASE Fingerprint, leads to a spikey energy structure modulation on the order of the coherence length on the electron bunches. Using a dispersion section and an additional radiator this modulation can be used to recreate the SASE pulse envelope in a different wavelength regime (optical afterburner radiation) [1].

Using this unique feature, at the Free Electron Laser in Hamburg (FLASH) we demonstrated that the pulse duration of an XUV FEL can be obtained using standard laser diagnostics (i.e. FROG). Cross correlation with a multitude of different methods show best agreement down to several femtoseconds. [2]

Future development reaches from online pulse duration measurement to amplification and jitter-free pump probe experiments.

References

[1] E.L. Saldin, E.A. Schneidmiller and M.V. Yurkov, Phys. Rev. ST Accel. Beams 13, 030701 (2010)

[2] T. Golz, Thesis: Pulse duration measurements at 4th generation X-ray light sources – Frequency Resolved Optical Gating at FLASH (2012)

8778-44, Session PS

Photon beam diagnostics at flash

Guenter Brenner, S. Bonfigt, Markus Braune, Ulf Jastrow, Barbara Keitel, Svea Kreis, Hendrik Kuhn, Deutsches Elektronen-Synchrotron (Germany); Matthias Markert, Qimonda Dresden GmbH & Co. OHG (Germany); Andrei A. Sorokin, Physikalisch-Technische Bundesanstalt (Germany); Kai Tiedtke, Deutsches Elektronen-Synchrotron (Germany)

Diagnostic tools to measure and provide important FEL photon beam parameters during FEL-commissioning and user experiments are crucial for tuning, stabilization and optimization of the FEL. In particular a pulse-resolved photon beam characterization is essential for most user experiments. Besides this, the unique properties of FEL radiation properties such as extremely high peak powers and short pulse lengths makes the shot-to-shot monitoring of important parameters very challenging. Therefore sophisticated concepts have been developed and used at FLASH in order to measure radiation pulse intensity, beam position and spectral as well as temporal distribution – always coping with the highly demanding requirements of user experiments as well as machine operation. Here an overview on the photon diagnostic devices operating at FLASH will be presented, with emphasizes on the pulse resolving intensity and energy detectors based on photoionization of rare gases (GMD, OPIS), the online VLS grating spectrometer for wavelength determination, the compact Hartmann wave front sensor, and the beam split & delay unit for FEL pulse duration diagnostics.

8778-45, Session PS

FLASH 2 photon diagnostics and beamline concepts

Marion Kuhlmann, Elke Plönjes, Deutsches Elektronen-Synchrotron (Germany)

FLASH 2 is an additional undulator beamline which is added to the soft X-ray free electron laser FLASH at DESY to turn it into a multi-beamline FEL user facility. Years of experience as single user facility have high impact on the planned photon diagnostics. Online measurements of intensity, position, wavelength, wavefront, and pulselength are optimized as well as photon beam manipulation tools, e.g. gas absorber, filters. The upgrade of FLASH with FLASH 2 is the direct consequence of the user community's high interest to operate in the water window and at the L- absorption edges of transition metals. Efforts are made that the beamline system will be set up to cover a wide wavelength range with beamlines capable to deliver down to the 5th harmonic at 0.8 nm and 1st harmonics in the water window. In addition, other beamlines will cover the longer wavelengths from 6 nm up to 40 nm and beyond. While proven concepts like pump-and-probe facilities are taken over from the current operation scheme, additional permanent endstations and user discipline specialized components are foreseen.

8778-46, Session PS

Multilens interferometry as an X-ray beam diagnostic technique

Mikhail Lyubomirskiy, Irina I. Snigireva, Gavin Vaughan, Anatoly A. Snigirev, European Synchrotron Radiation Facility (France); Victor G. Kohn, Russian Research Ctr. Kurchatov Institute (Russian Federation); Sergey Kuznetsov, Vyacheslav Yunkin, Institute of Microelectronics Technology and High Purity Materials (Russian Federation); Petr Ershov, , Immanuel Kant Baltic Federal Univ. (Russian Federation)

Recently a new bilens interferometer based on Si planar refractive lenses was proposed [1]. An interference pattern, which forms by a bilens interferometer, is rather simple and similar to that in Young's experiment and can be used for coherent beam diagnostic techniques. To extend the functional possibilities of a bilens interferometer technique we propose a multilens system. Increasing a beam acceptance up to millimetres may allow extracting information not only on the effective source size-spatial coherence, but also of the wavefront shape. In comparison with the bilens interferometer a multilens system forms a more complicated interference pattern which can be described in the Talbot imaging concept.

The main target of the work was to study far field interferometer properties of the multilens interferometer. The experiment was performed at the long (~100 m) ID11 beamline at the ESRF in the energy range 32-64 keV. An interference pattern was recorded at a distance of 52 meters from an interferometer, which was at a distance of 42.5 meters from the source. This geometry allowed us to observe the fundamental and phase-inverse Talbot images. An effective source size of 15 microns (FWHM) was determined by analyzing these images. To validate the results, two other techniques were used: direct and indirect. The first method was based on the direct measurements of the source images produced by 2D refractive lenses [2]. The indirect method involved analysis of the interference pattern from a Boron fiber [3]. An effective source size was calculated by solving an inverse problem where a variable parameter was the source size. Results from all three techniques are in good agreement. It should be noted that in a near field mode a multilens interferometer can be used for a wave diagnostics like the Shack Hartmann wavefront sensor [4].

[1] A. Snigirev, I. Snigireva, V. Kohn, V. Yunkin, S. Kuznetsov, M. Grigoriev, T. Roth, G. Vaughan, C. Detlefs: X-Ray nanointerferometer based on Si refractive bilenses. Phys. Rev. Letters 103, 064801, 2009.

[2] T. Weitkamp, O. Chubar, M. Drakopoulos, A. Souvorov, I. Snigireva, A. Snigirev, F. Gunzler, C. Schroer, B. Lengeler, Refractive lenses as a beam diagnostics tool for high-energy synchrotron radiation, Nuclear Instruments and Methods in Physics Research A 467–468 248–251 (2001)

[3] O.Chubar, A.Snigirev, S.Kuznetsov, T.Weitkamp, V.Kohn, X-RAY INTERFERENCE METHODS OF ELECTRON BEAM DIAGNOSTICS, Proceedings DIPAC 2001 – ESRF, Grenoble, France

[4] R. Shack and B.C. Platt, Production and use of a lenticular Hartmann screen, J.Opt. Soc. Am. Vol. 61, p. 656. (1971).

8778-47, Session PS

Design of a three-dimensional Ionization Profile Monitor (IPM)

Heiko Breede, Martin Sachwitz, Hans-Jürgen Grabosch, Florian Perlick, DESY (Germany)

The Free Electron Laser FLASH at the German Electron Synchrotron (DESY) in Hamburg is a linear accelerator, which uses superconducting technology to produce soft x-ray laser light ranging from 4 to 30 nm. To ensure the operation stability of FLASH, monitoring of the beam is mandatory. Among various detectors located at the beam pipe, two Ionization Profile Monitors (IPM) detect the lateral x and y position changes. The functional principle of the IPM is based on the detection of electrons, generated by interaction of the photon beam with the residual gas in the beam line.

The newly designed IPM enables the combined determination of the FEL's horizontal and vertical position as well as the beam's profile. This is made possible by a compact monitor, consisting of a cage in a vacuum chamber, two micro-channel plates (MCP) and two structural repeller plates with toggled electric fields at the opposite sides of the MCPs. The electrons created by the FEL beam, drift in a homogenous electrical field towards the respective micro-channel plate, which produces an image of the beam profile on an attached phosphor screen. A CCD camera for each MCP in combination with a computer is used for the evaluation. This indirect detection scheme operates over a wide dynamic range and allows the detection of the center of gravity and the shape of the photon beam without affecting the FEL beam. Exact knowledge of the path taken by the electrons permits a recursive determination of the beam position. Within a beam variance of less than 10 mm, an accuracy better than ±8?m seems to be possible.

8778-48, Session PS

An electron beam detector for the FLASH II beam dump

Florian Perlick, James Good, Nicole Leuschner, Gero Kube, Martin Sachwitz, Michael Schmitz, Kay Wittenburg, Torsten Wohlenberg, DESY (Germany)

After the generation of the laser light, a dipole deflects the highly energetic electron beam of FLASH (Free Electron Laser Hamburg) into a dump. A detector is developed to control the position, dimensions and profile of the electron beam and to avoid beam contact with vacuum components, causing a total breakdown of the Linac. Scintillation light is emitted due to the electrons hitting a luminescent screen (Al_2O_3:Cr) located in front of the dump window. This light is then reflected by a mirror, located in 2 m distance from the screen, and passes through a vacuum window, perpendicular to the electron beam. A CCD camera is used for the optical analysis of the beam image. To prevent the camera from being damaged by radiation, it is located about 1.5 meters away from the beam line on top of the concrete and additionally protected by lead shielding.

To coordinate the interaction of the screen with the light guiding system and the camera, an experimental setup has been built up in a lab. The design and the terms of installation of the components correspond to FLASH, while a 5 keV gun serves as electron source. For guiding the light, two different techniques will be examined: a conventional lens-mirror-system and radiation-hard optical fibres. For the latter it is planned to test the impact of radiation on their optical qualities by installing them onto a “radioactive hot spot” at the bunch compressor in the FLASH accelerator. It will be shown that the resolution of the entire optical system is better than 1 mm.

8778-49, Session PS

Ultrafast pump-probe X-ray diffraction and spectroscopy at SwissFEL

Chris J Milne, Gerhard Ingold, Paul Beaud, Bill Pedrini, Luc Patthey, Bruce D Patterson, Rafael Abela, Paul Scherrer Institut (Switzerland)

With their unique combination of high per-pulse X-ray flux and femtosecond pulse durations, hard x-ray free electron lasers are an almost ideal source for time-resolved structural experiments. The recently approved SwissFEL will be capable of generating femtosecond hard x-rays pulses in the photon energy range of 2-12 keV, with a planned emphasis on performing femtosecond pump-probe measurements.[1] SwissFEL will take advantage of the significant local expertise at the Paul Scherrer Institute in time-resolved X-ray measurements,[2-10] X-ray spectrometer development,[11-13] and X-ray detector development.[14-17] Experimental Station A (ESA) of the SwissFEL will focus on probing the ultrafast dynamics of systems in solution using a combination of X-ray spectroscopy and scattering.[18] The primary goal of ESA will to enable users to perform X-ray absorption (XAS) and emission (XES/RIXS) spectroscopy pump-probe experiments over the full energy range with <50 fs time resolution (FWHM) using a range of excitation wavelengths (UV to IR). ESA will also be capable of using advanced methods for the injection of aerosol particles and sub-micron protein crystals. Experimental Station B (ESB) will focus on probing ultrafast dynamics in condensed matter using X-ray diffraction. The primary goal of ESB will be to perform grazing-incidence diffraction measurements under vacuum with <50 fs time resolution (FWHM) in a variety of experimental conditions, including low temperature (10 K), with a focus on THz excitation. This talk will provide an overview of the techniques we expect to have available at ESA and ESB as well as the scientific problems we hope to address.

1. Patterson, B. D. et al. New J Phys 12, 035012 (2010).
2. Beaud, P. et al. Phys Rev Lett 99, – (2007).
3. Johnson, S. L. et al. Phys Rev Lett 100, – (2008).
4. Johnson, S. L. et al. Phys Rev Lett 102, – (2009).
5. Johnson, S. L. et al. Acta Crystallogr A 66, 157–167 (2010).
6. Beaud, P. et al. CHIMIA 65, 308–312 (2011).
7. Bressler, C. & Chergui, M. Annu Rev Phys Chem 61, 263–282 (2010).
8. Chergui, M. Acta Crystallogr A 66, 229–239 (2010).
9. Bressler, C. et al. Science 323, 489–492 (2009).
10. Pham, V.-T. et al. J Am Chem Soc 133, 12740–12748 (2011).
11. Szlachetko, J. et al. Rev Sci Instrum 83, 103105 (2012).
12. Szlachetko, J. et al. Chem Commun 48, 10898 (2012).
13. Kleymenov, E. et al. Rev Sci Instrum 82, – (2011).
14. Schmitt, B. et al. Nucl Instrum Meth A 518, 436–439 (2004).
15. Bergamaschi, A. et al. J Synchrotron Rad 17, 653–668 (2010).
16. Becker, J. et al. Nuclear Inst. and Methods in Physics Research, A 694, 82–90 (2012).
17. Bergamaschi, A. et al. J Synchrotron Rad 18, 923–929 (2011).
18. Patterson, B. D. & Abela, R. Phys. Chem. Chem. Phys. 12, 5647–5652 (2010).

8778-50, Session PS

Characterization of the temporal coherence of short intense XUV sources with a wavefront-division interferometer

Annie Klisnick, Limin Meng, A. Le Marec, Univ. Paris-Sud 11 (France)

X/XUV FELs and plasma-based XUV lasers (PXUVLs), which are based on Amplification of Spontaneous Emission (ASE or SASE), are characterized by a short duration (10s of fs for FELS to several ps for PXUVLs) that is comparable but still larger than the coherence time of the source. In plasma-based XUV lasers, the temporal coherence is related to the spectral properties of the highly charged ions, which emit the lasing line. For both XFEL and PXUVL sources, an accurate characterization of the temporal coherence is important because it controls the temporal structure of the pulse.

Over the last few years we have carried out a comprehensive experimental study of the temporal coherence of all currently operational plasma-based XUV lasers, developed in several laboratories worldwide [1, 2, 3, 4]. The main motivation of our work was to explore their potential for amplification of femtosecond high-order harmonic pulses to reach higher peak power. Our measurements are based on a Fresnel wavefront-division interferometer, including a pair of grazing incidence di-hedrons, specifically designed for that purpose. Our configuration is slightly different from the one used in [5] to characterize the temporal coherence of the FLASH XUV-FEL pulse.

We have found that the measured coherence time of the different plasma-based XUV lasers can vary between 0.7 and 5 ps. Comparison with numerical simulations show that the observed differences are related to the local plasma conditions (density, temperature) in the gain region [6].

In this paper we summarize the capabilities of the interferometer in connection with the main results obtained. We discuss its potential to characterize the temporal coherence of XUV FEL pulses, for which the expected temporal coherence is much shorter, significantly less than 100 fs.

[1] F. Tissandier et al., Phys. Rev. A 81, 063833 (2010)
[2] L. Meng et al., Opt. Express 19, 12087 (2011)
[3] L. Urbanski et al., Phys. Rev. A 85, 033837 (2012)
[4] M. Meng et al, Proc. of 13th International Conference on X-ray Lasers, Springer (2013) in press
[5] W.F. Schlotter et al., Opt. Letters 35, 372 (2010)
[6] A. Klisnick et al., 16th International Workshop on Radiative Properties of H

8778-51, Session PS

A split- and delay unit for the European XFEL

Sebastian Roling, Westfälische Wilhelms-Univ. Münster (Germany); Stefan Braun, Peter Gawlitza, Fraunhofer IWS Dresden (Germany); Liubov Samoylova, European XFEL

GmbH (Germany); Björn Siemer, Westfälische Wilhelms-Univ. Münster (Germany); Frank Siewert, Helmholtz-Zentrum Berlin für Materialien und Energie GmbH (Germany); Harald Sinn, European XFEL GmbH (Germany); Frank Wahlert, Michael Wöstmann, Helmut Zacharias, Westfälische Wilhelms-Univ. Münster (Germany)

For the European XFEL an x-ray split- and delay-unit (SDU) is built covering photon energies from 5 keV up to 20 keV. This SDU will enable time-resolved x-ray pump / x-ray probe experiments as well as sequential diffractive imaging on a femtosecond to picosecond time scale. Further, direct measurements of the temporal coherence properties will be possible by making use of a linear autocorrelation. The set-up is based on geometric wavefront beam splitting, which 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 Ni/B4C multilayers. Both partial beams will then pass variable delay lines. For different wavelengths the angle of incidence onto the multilayer mirrors will be adjusted in order to match the Bragg condition. For a photon-energy of h? = 20 keV a grazing angle of ? = 0.57° has to be set, which results in a footprint of the beam (6?) on the mirror of l = 96 mm. At this photon energy the reflectance of a Mo/B4C multilayer coating with a multilayer period of d = 3.2 nm and N = 200 layers amounts to R = 0.92. For a photon energy of h? = 5 keV a smaller size of the footprint of l = 65 mm is calculated due to the steeper grazing angle of ? = 2.28°. In order to enhance the maximum transmission for photon energies below h? = 10 keV, a Ni/B4C multilayer coating can be applied beside the Mo/B4C coating for this spectral region. Because of the different incidence angles, the path lengths of the beams will differ as a function of wavelength. Hence, maximum delays between +/- 2.5 ps at h? = 20 keV and up to +/- 23 ps at h? = 5 keV will be possible.

8778-18, Session 4

LCLS accelerator operation and measurement of electron parameters relevant for the x-ray beam *(Invited Paper)*

Henrik Loos, SLAC, Stanford Univ. (United States)

The Linac Coherent Light Source (LCLS) as the world's first hard x-ray free electron laser in the range of 250 eV to 10 keV at its fundamental wavelength has been operated as a user facility since 2009 with now 6 experimental stations and an increasing range of x-ray beam parameters available to users. Various aspects of operating the LCLS accelerator to deliver the necessary electron beam in terms of bunch charge, energy, and length for the wide parameter range and different FEL operating modes will be discussed. An emphasis will be on the electron beam diagnostics that are most critical for generating the desired x-ray beam properties. Measurements of electron beam energy, energy loss, and transverse orbit will be shown as well as bunch duration and shape measurements.

*Work supported by DOE contract DE-AC02-76SF00515

8778-19, Session 4

Comparison of instrumentation for the longitudinal electron bunch profile *(Invited Paper)*

Rasmus Ischebeck, Paul Scherrer Institut (Switzerland)

X-ray FELs make use of compressed electron bunches to generate the X-ray pulses.From the cathode to the undulators, the electron bunch length is reduced by two to six orders of magnitude, depending on the accelerator design.

Numerous diagnostics concepts are required for this broad range, and several instruments have been developed to measure the electron bunch length and to monitor the compression process.

The desired operation mode of the instrument, ranging from dedicated measurement devices that consume the beam, to on-line monitors that operate continuously during user runs, also influence the choice of diagnostics concept.

A broad overview of these concepts will be presented, and their features are compared.

Different types of instrumentation have been evaluated when designing a longitudinal diagnostics suite for SwissFEL. The motivation behind this choice will be described, and the present status of the implementation will be presented.

8778-20, Session 4

Femtosecond-precision stabilisation of the electron bunch arrival time over a large range of bunch charges for FLASH and the European XFEL

Marie Kristin Czwalinna, S. Pfeiffer, H. Schlarb, C. Schmidt, Sebastian Schulz, Cezary Sydlo, Jaroslaw Szewinski, Deutsches Elektronen-Synchrotron (Germany); Wojciech Jalmuzna, Technical Univ. Lodz (Poland); A. Kuhl, Technische Univ. Darmstadt and DESY (Germany); Aleksandar Angelovski, Andreas Penirschke, Technische Univ. Darmstadt (Germany)

For time-resolved user experiments and for seeding schemes at free-electron lasers the precise measurement and regulation of the bunch arrival time as well as compression are key requirements. The four bunch arrival time monitors (BAM) presently installed at FLASH allow for timing measurements with sub-10fs resolution for bunch charges above 200 pC. The reference time frame is provided by the master laser oscillator of the optical synchronisation system.

Beam-based measurements of arrival time and compression are incorporated into a longitudinal, intra-train stabilisation scheme acting on specific acceleration modules. The modulation of the RF set-point in a direct feedback loop with an optimised controller already allowed for a reduction of the arrival time jitter to below 20 fs.

Future user experiments increasingly demand for a reduction of the FEL pulse duration, requiring lower bunch charges down to 20 pC in case of FLASH and the European XFEL. For expanding the detection scheme involved in the BAMs to this low charge regime while maintaining the sub-10 fs resolution, a new pick-up sytem with an RF bandwidth of 40 GHz has been developed and installed lately.

In this paper we present the current status and on-going developments of the arrival time measurememt and stabilisation system.

8778-21, Session 4

Longitudinal bunch profile diagnostics with coherent radiation at FLASH

Eugen Hass, Univ. of Hamburg (Germany); S. Wesch, The Helmholtz Zentrum Berlin (Germany); Christopher Gerth, Deutsches Elektronen-Synchrotron (Germany); M. Yan, B. Schmidt, DESY (Germany)

The required high peak current in free-electron lasers (FELs) is realized by longitudinal compression of the electron bunches to sub-picosecond length. A novel in-vacuum polychromator (CRISP4) has been developed for measuring coherent radiation in the THz and infrared range. The polychromator is equipped with _ve consecutive dispersion gratings and 120 parallel readout channels; it can be operated either in short (5 - 44 _m) or in long wavelength mode (45 - 430 _m). Fast parallel readout permits the monitoring of coherent radiation from single electron bunches. Due to the large wavelength range covered and the superb absolute calibration of the device, Kramers-Kronig based phase retrieval allows to online reconstruct a longitudinal bunch pro_le from the measured coherent radiation spectrum. The device is used as a bunch length monitoring and tuning tool during routine operation at FLASH. Comparative measurements with the RF transverse deecting resonator show excellent agreement of both methods.

8778-22, Session 5

Arrival time diagnostic using free carriers generation induced by X-ray FEL *(Invited Paper)*

M. Harmand, LULI, Ecole Polytechnique (France); Robert Riedel, A. A. Shemmary, DESY (Germany); Mina R. Bionta, Ryan N. Coffee, Mattieu Chollet, Doug French, David Mark Fritz, SLAC National Accelerator Lab. (United States); M. Gensch, Torsten Golz, DESY (Germany); Henrik T. Lemke, SLAC National Accelerator Lab. (United States); N. Medvedev, M. J. Prandolini, DESY (Germany); Klaus Sokolowski-Tinten, Univ. Duisburg-Essen (Germany); Nicola Stojanovic, Sven Toleikis, Ulrike Wegner, Deutsches Elektronen-Synchrotron (Germany); Diling Zhu, SLAC National Accelerator Lab. (United States); Beata Ziaja-Motyka, Franz Tavella, Deutsches Elektronen-Synchrotron (Germany); Marco Cammarata, SLAC National Accelerator Lab. (United States)

With the advance of few-femtosecond FEL pulses, the possibility to study ultrafast physical processes is not far off. Coupled with available sub-10 fs optical pulses in pump – probe schema, the objective is now to investigate few-femtosecond dynamics. However, synchronization between optical lasers and X-ray pulses are still challenging and limited by the shot-to-shot fluctuation of their respective arrival time (the so-called « jitter »). We report the development of "measure-and-sort'" approach using a versatile single-shot diagnostic based on ultrafast free-carrier generation in optically transparent materials. Studies have been performed in the hard X-ray regime at LCLS and in the VUV-soft X-ray regime at FLASH.

At LCLS, we have demonstrated that the change of the optical properties is strong enough to allow such measurements in the hard X-ray regime. By correlating two independent measurements, we demonstrate unambiguously a sub-10 fs rms error in reporting the optical/X-ray arrival time. The single shot error suggests the possibility of reaching fewfemtosecond resolution [1]. At FLASH, we have also shown the possibility to extract the FEL pulse duration from such timing tools. We have performed FEL pulse duration measurements at two distinct FEL wavelengths, 41.5 nm and 5.5 nm [2]. In both cases, we demonstrate the possibility of a non damaging mode allowing to operate the timing tools as an online diagnostic.

[1] M. Harmand et al, Nature Photonics, accepted (2013)

[2] R. Riedel et al, Submitted.

8778-23, Session 5

Single shot spectral measurements for time diagnostic *(Invited Paper)*

Makina Yabashi, Yuichi Inubushi, RIKEN (Japan); Tetsuji Katayama, Tadashi Togashi, Japan Synchrotron Radiation Research Institute (Japan); Takashiro Sato, RIKEN (Japan); Kensuke Tono, Japan Synchrotron Radiation Research Institute (Japan)

Temporal diagnostics of XFEL pulses are highly important for various applications. For evaluating pulse duration, we have performed high-resolution measurement of XFEL spectra with an energy resolution of 14 meV at 10 keV. By comparing the observed spectra with those given by an XFEL simulation code, SIMPLEX, the pulse durations have been determined to be 4.5 to 31 fs with a reasonable accuracy [1]. We are trying to apply this technique to realize X-ray absorption spectroscopy in dispersive geometry, which could provide new opportunities in ultrafast spectroscopic researches.

[1] Y. Inubushi et al, Phys. Rev. Lett. 109, 144801 (2012).

8778-24, Session 5

Towards diagnostics of spectral and temporal pulse properties for the European XFEL

Jan Grünert, Jens Buck, Cigdem Ozkan, Wolfgang Freund, Marc Planas, Serguei Molodtsov, European XFEL GmbH (Germany)

The European X-ray Free Electron Laser (XFEL.EU) will be a 4th generation light source for research of at the same time extremely small structures (sub-Ångström resolution) and extremely fast phenomena (femtosecond resolution). Compared to 3rd generation synchrotron sources its radiation will show much narrower bandwidth - of the order of dE/E~10E-3 - which many experiments will directly exploit without further monochromatization. However, the shot noise at the origin of the radiation-creating Self-Amplified Spontaneous Emission (SASE) process leads to significant pulse-to-pulse variations of intensity, spectrum, wavefront, and temporal properties, so that monitoring of these properties is mandatory for user experiments. Experiments at this facility will use the particular spectral properties, and also employ pump-probe schemes, where the shot-to-shot delay time between X-rays and an optical laser is required for data interpretation.

The extreme brilliance and resulting single-shot damage potential are difficult to handle for any XFEL diagnostics. Apart from the large energy range of operation of the facility from 280 eV to 25 keV in FEL fundamental, the particular challenge for the European XFEL diagnostics is the high intra bunch train photon pulse repetition rate of 4.5 MHz, potentially causing additional damage by high heat loads and making shot-to-shot diagnostics very demanding. This presentation reports on the facility concepts and recent progress in method and instrumentation development, focusing on the diagnostics of spectral and temporal properties.

8778-25, Session 5

Ultrafast laser synchronization at the FERMI@Elettra FEL

Paolo Sigalotti, Paolo Cinquegrana, Alexander A. Demidovich, Rosen Ivanov, Ivaylo Nikolov, Miltcho B. Danailov, Elettra-Sincrotrone-Trieste S.C.p.A. (Italy)

Modern VUV and X-ray Free Electron Laser (FEL) facilities contain a number of ultrafast lasers (like photoinjector, seed and pump-probe lasers) whose performance is crucial for the generated FEL light quality as well as for the accuracy of the time resolved measurements performed using the FEL pulses. One of the very important laser related aspects, especially at seeded FELs, is the ability to precisely lock the ultrafast laser systems to the master clock signal, keeping the timing jitter and drifts of the generated pulses with respect to the machine timing as low as possible. The aim of this work is to review the main sources of timing jitter and drifts and present the schemes and solutions developed at FERMI for their characterization and compensation. The paper will first introduce a general scheme showing the architecture of the laser locking system developed for FERMI. Both the radio-frequency (RF) locking and the advanced balanced optical cross correlator electronics and optical setup design are described, together with data on the laser oscillator locking performance obtained in different modalities. Cross correlation measurements indicating the contribution of the ultrafast regenerative amplifier and optical beam transport part to the overall temporal jitter of the amplified ultrashort pulses arriving at destination are presented. The paper also includes examples of the influence of improved laser timing jitter and drifts on the seeded FEL performance and discusses foreseen future developments.

8778-26, Session 5

Femtosecond-precision synchronization of the pump-probe optical laser for user experiments at FLASH

Sebastian Schulz, Marie Kristin Czwalinna, Matthias Felber, Deutsches Elektronen-Synchrotron (Germany); Pawel Predki, Technical Univ. of Lodz (Poland); Sven Schefer, Univ. Hamburg (Germany); H. Schlarb, Ulrike Wegner, Deutsches Elektronen-Synchrotron (Germany)

Pump-probe user experiments carried out at a free-electron laser like FLASH or the European XFEL in conjunction with an optical laser require a synchronization down to the few-femtosecond level between the laser and the X-ray light pulses produced by the accelerator. Similarly, for externally seeded operation of the free-electron laser, the seed radiation has to be synchronized with a timing jitter at least in the order of the electron bunch duration, ideally better.

In this paper, we present the long-term stable synchronization of the FLASH pump-probe Ti:sapphire oscillator and an optical reference with sub-10 fs (rms) timing jitter employing a balanced optical cross-correlator. The reference pulse train, transmitted over an actively transit time-stabilized 500 m fiber link, is generated by the FLASH master laser oscillator. This laser also provides the reference for several electron bunch arrival time monitors with sub-10 fs resolution, which in turn enable a longitudinal feedback reducing the electron bunch arrival time jitter to below 25 fs (rms). Combining the precise synchronization of the laser and the longitudinal accelerator feedback enabled a proof-of-principle pump-probe experiment at FLASH, ultimately showing a significant reduction of the timing jitter between the optical laser and the XUV pulses generated by the FEL, compared to the present standard operation.

8778-27, Session 6

Femtosecond optical/hard x-ray timing diagnostics at an FEL: implementation and performance *(Invited Paper)*

Henrik T. Lemke, SLAC National Accelerator Lab. (United States); Marco Cammarata, Institut de Physique de Rennes (France); Marion Harmand, Deutsches Elektronen-Synchrotron (Germany); Ryan N. Coffee, Matthieu Chollet, Joseph Robinson, Diling Zhu, Mina R. Bionta, David M. Fritz, James M. Glownia, SLAC National Accelerator Lab. (United States)

The development of Free Electron Lasers has opened the possibility to investigate ultrafast processes using femtosecond hard x-ray pulses. In optical/x-ray light pump/probe experiments, however, the time resolution is mainly limited by the ability to synchronize both light sources over a long distance (>100 fs FWHM) rather than their pulse length (>10 fs FWHM).

We have implemented a spectrally encoding x-ray to optical laser timing diagnostic into the XPP beamline at LCLS with a timing uncertainty down to 10 fs. An x-ray induced change of refractive index in a solid target is temporally probed for single pulses by a chirped white light pulse [1]. By resorting single shot data to the timestamps obtained by the diagnostics, the temporal data quality can be be improved to basically pulse length limited time resolution. By interchangable targets and adjustable x-ray and laser foci, the method was successfully applied for very different X-ray parameters. These are different photon energies in the range of 6-20 keV, which at LCLS also includes application of 3rd Harmonic radiation, pulse energy, and bandwidth, when using a Si(111) monochromator.

[1] Proc. SPIE 8504, X-Ray Free-Electron Lasers: Beam Diagnostics, Beamline Instrumentation, and Applications, 85040M (October 15, 2012); doi:10.1117/12.929097

8778-28, Session 6

Sample refreshment schemes for high repetition rate FEL experiments *(Invited Paper)*

Joachim Schulz, European XFEL GmbH (Germany)

Free-electron lasers offer a variety of unique properties for spectroscopy and imaging. The combination of high peak brilliance and a high repletion rate opens a window to experiments that have not been feasible so far but also introduces challenges in sample preparation and refreshment.

First experiments at the Linac Coherent Light Source (LCLS) in Stanford showed the potential of free electron lasers for serial x-ray crystallography [1] as well as for imaging non-reproducible objects [2]. Owing to the superconducting accelerator technology, the European X-ray Free-Electron Laser Facility (Eur. XFEL) will allow an average repetition rate of up to 27 kHz with bunch separation in the order of 200 nanoseconds. This extremely high repetition rate gives great chances for the scientific impact of the European XFEL, but is also comes with challenges for providing fresh samples for each bunch.

This contribution will give an overview of the sample environment techniques that are in consideration for the European XFEL Facility. Biological samples, such as virus particles or nano-sized protein crystals, will be introduced in the instruments in liquid jets and from aerosol by means of an aerodynamic lens. Liquid jets will also come into operation for studying inelastic x-ray scattering on chemical reactions in the liquid phase. For various imaging and spectroscopic experiments, solid state targets are going to be relevant. Here the development of fast sample delivery systems is exceedingly difficult. For magnetic scattering and studying phase transitions it is furthermore necessary to combine these techniques with magnetic fields and with temperature control.

The European XFEL Facility is setting up a sample environment group to develop state of the art sample handling technology. This contribution will give an overview of the status of the considerations and an outlook into the future of sample refreshments schemes for high repetition rate FEL experiments.

[1] Henry N. Chapman et al. Nature 470, 73 (2011)

[2] M. Marvin Seibert at al. Nature 470, 78 (2011)

8778-29, Session 6

Status of detector development for the European XFEL

Jolanta Sztuk-Dambietz, Markus Kuster, Andreas Koch, Monica Turcato, Steffen Hauf, European XFEL GmbH (Germany)

The European X-ray Free Electron Laser (EuXFEL) will provide as-yet-unrivaled peak brilliance and ultrashort pulses of spatially coherent X-rays with a pulse length of less than 100 fs in the energy range between 0.25 and 25 keV. The high radiation intensity and ultra-short pulse duration will open a window for novel scientific techniques and will allow to explore new phenomena in biology, chemistry, material science, of matter at high energy density, in atomic, ion and molecular physics.

The variety of scientific applications and especially the unique XFEL time structure will require adequate instrumentation to be developed in order to exploit the full potential of the light source. To make optimal use of the unprecedented capabilities of the European XFEL and master these vast technological challenges, the European XFEL GmbH has started a detector R&D program. The technology concepts of the detectors system presently under development are complementary in their performance and will cover the performance requirements of a large fraction of scientific applications envisaged for the EuXFEL facility. The actual status of the detector development projects which includes ultra-fast 2D imaging detectors, low repetition rate 2D detectors as well as strip detectors for e.g. spectroscopy applications will be presented. Furthermore, an overview and outlook over the forthcoming implementation phase of the European XFEL in terms of detector R&D will be given.

SPIE Optics+ Optoelectronics

8778-30, Session 6

The AGIPD detector for the European XFEL

Laura Bianco, Deutsches Elektronen-Synchrotron (Germany)

The Adaptive Gain Integrating Pixel Detector (AGIPD) is a hybrid pixel detector developed to be used at the European XFEL by a consortium consisting of Deutsches Elektronensynchrotron (DESY), Paul-Scherrer-Institut (PSI), University of Hamburg and University of Bonn.

The European XFEL will generate extremely brilliant pulses of X-rays organized in pulse trains consisting of 2700 pulses with >1012 photons of 12keV each, 100fs long and with a 220ns spacing running at 10Hz repetition rate.

The detector designed to be running with this beam will have to face several challenges: the dynamic range has to cover the detection of single photons and extend up to >104photons/pixel in the same image, and as many images as possible have to be recorded in the pixel to be read out between pulse trains.

Due to the high flux, the detector will have to withstand a dose up to 1GGy integrated over 3 years.

The AGIPD collaboration developed a charge integrating pixel detector consisting of 1Mpixel hybrid pixel detector featuring a pitch of 200?m, dynamic gain switching and analogue on-pixel storage chain with a radiation hard design.

The readout chip will consist of 64x64 pixels and the detector will be built out of 4 quadrants having 4 modules each containing a silicon sensor bump bonded to an array of 8 x 2 CMOS readout chips.

This talk will give an overview of the AGIPD project, including some results of the latest AGIPD prototype chips.

8778-31, Session 6

Instrument for single-shot X-Ray emission-spectroscopy experiments

Luca Poletto, Marcello Coreno, Consiglio Nazionale delle Ricerche (Italy); Andrea Di Cicco, Univ. degli Studi di Camerino (Italy); Fabio Frassetto, Univ. degli Studi di Padova (Italy); Paolo Miotti, Consiglio Nazionale delle Ricerche (Italy); Salvatore Stagira, Politecnico di Milano (Italy)

We present the design and characterization of a portable and compact photon spectrometer to be installed in free-electron-laser beamlines for photon in-photon out experiments, in particular single-shot X-ray emission spectroscopy. The instrument is operated in the 30-800 eV energy range and will be initially used in the LDM (Low-Density Matter) and TIMEX (TIme-resolved studies of Matter under EXtreme conditions) beamlines of FERMI@ELETTRA, covering the whole spectral range of FERMI-1 and FERMI-2 emissions. The design of the instrument is tailored to achieve high spectral resolution in the whole interval of operation, high acceptance angle and high dynamic range. These characteristics are achieved in a compact environment to give a portable instrument that may be easily installed in different experimental chambers. The design consists of an entrance slit, a grazing-incidence diffraction grating and a detector. The number of elements within the optical path is kept to one component, to minimize the losses due to reflectivity. The grating is spherical with variable line spacing along its surface, to provide an almost flat spectral focal plane that is perpendicular to the direction of the diffracted light. The detector is a back-illuminated CCD. The spectral resolution is better than 0.2% in the 30-800 eV region and the acceptance angles are 10 X 50 mrad in the 30-250 eV and 5 X 50 mrad in the at 250-800 eV. The design and characterization of the instrument will be discussed.

8778-32, Session 6

Coherent diffraction imaging project at FERMI@Elettra: first commissioning results and research opportunities

Flavio Capotondi, Sincrotrone Trieste S.C.p.A. (Italy); Filippo Bencivenga, Synchrotron Trieste S.C.p.A. (Italy); Miltcho B. Danailov, D. Fausti, Luca Giannessi, Emanuele Pedersoli, Nicola Mahne, Lorenzo Raimondi, Cristian Svetina, Marco Zangrando, Maya Kiskinova, Sincrotrone Trieste S.C.p.A. (Italy); Sasa Bajt, Miriam Barthelmess, Holger Fleckenstein, Henry N. Chapman, Deutsches Elektronen-Synchrotron (Germany); Joachim Schulz, European XFEL GmbH (Germany); S. Schleitzer, Lutz Müller, DESY (Germany); Carsten Nils Gutt, Heidelberg School of Medicine (Germany); Gerhard Gruebel, Deutsches Elektronen-Synchrotron (Germany)

The high transverse coherence and peak brightness of ultra-short SASE-FEL pulses have already demonstrated the extraordinary potential for coherent diffraction imaging (CDI) in a single shot experiment before the radiation damage of the sample is manifested [1]. The limitations imposed by the partial longitudinal coherence of SASE-FEL for getting selective chemical information using single shot resonant (R-) CDI, should be overcome by the seeded FEL (S-FEL) sources, as FERMI@Elettra [2]. This opens unique opportunities for single-shot R-CDI experiments with access to elemental and/or magnetic structure of morphologically complex targets using the energy tunability and multiple (circular or linear) polarization of the fully coherent seeded FEL pulses.

The measurement station for CDI, operating at the DiProI beamline of the FERMI@Elettra, is designed to meet the requirements for performing a wide range of static and dynamic studies and has been already commissioned using both synchrotron and FEL radiation [3]. This presentation will report the first CDI measurements illustrating the present performance of the measurement station in single-shot CDI and the advent of tunability and multiple polarization of the FERMI pulses in resonant magnetic scattering at Co M-absorption edges [4]. Finally, the unprecedented opportunity for jitter-free FEL pump-FEL probe time resolved CDI, opened by generation of two-color FEL pulses by the same electron bunch at FERMI-FEL, will be illustrated with the recent proof-of-of principle experiments using specially designed sample consisting of Ti grating.

[1] H. N. Chapman et al, Nature Physics 2, 839 - 843 (2006).

[2] E.Allarie et. al, Nature Photonics 6, 699-704 (2012)

[3] E. Pedersoli et al, Rev. Sci. Instrum. 82, 043711 (2011).

[4] F. Capotondi et al. in preparation.

8778-33, Session 6

High purity x-ray polarimetry

Kai Schulze, Helmholtz-Institut Jena (Germany) and Friedrich Schiller University Jena (Germany); Berit Marx, Friedrich Schiller University Jena (Germany); Ingo Uschmann, Friedrich Schiller University Jena (Germany) and Helmholtz-Institut Jena (Germany); Ralf Röhlsberger, HASYLAB at DESY (Germany); Gerhard G Paulus, Friedrich Schiller University Jena (Germany)

The polarization properties of undulator radiation are frequently used in magnetic scattering experiments. However, small polarization effects require a higher purity of the polarization state than an undulator can deliver. Such measurements are made possible by a high purity polarimeter consisting of perfect single crystals. An intensity ratio between the two polarization states of about 10 orders of magnitude was measured with multiple Bragg diffraction close to 45 degrees. With the help of this high purity polarimeter, extreme small polarisation changing effects can be detected. Therefore, high brilliant X-ray sources like the XFEL are required. In addition, the short duration of X-ray pulses enable time-resolved experiments, e.g. laser-pump X-ray probe experiments. One of them is the investigation of an effect predicted by quantum electrodynamics (QED), called vacuum birefringence. An ultra intense petawatt laser causes birefringence in vacuum and therefore, a small ellipticity in the former linear polarized X-ray probe pulses. Beside QED, also quantum optical effects based on nuclear resonances like electromagnetically induced transparency can be measured with polarimetry and could represent new possibilities to work at XFELs.

8778-34, Session 6

X-ray pump - probe experiments with MHz repetition rates

Wolfram Leitenberger, Hengameh Navirian, Univ. Potsdam (Germany); Roman Shayduk, Jewgeni Goldshteyn, Peter Gaal, Helmholtz-Zentrum Berlin (Germany); Matias Bargheer, Univ. Potsdam (Germany)

We present an experimental setup for ultrafast x-ray diffraction (UXRD) installed at the BESSY II storage ring. A pump laser excites the sample using 250 fs laser-pulses. It is synchronized to the synchrotron radio frequency at repetition rates ranging from 208 kHz to 1.25 MHz. The detection of diffracted X-rays is based on time correlated single photon counting. The set-up allows to observe transient lattice expansions with a time resolution of 10 to 100 ps within an time interval of up to 5 µs after laser excitation. The time resolution is limited by the duration of the X-ray pulses which depends on the operation mode of the storage ring. The accuracy of the determination of lattice expansions of up to 10?6 corresponds to transient temperature changes of 50 mK.

Further we discuss issues connected to the high heat-load of the sample due to high repetition rate laser pumping and an experiment aiming on the realization of a “pico X-ray switch” i.e. the shortening of X-ray pulses to a few ps based on X-ray diffraction on nm thick layered structures.

Finally we present the outlook for our future research after the installation of the new beam line optics which will increase the available photon number by more than a factor of 100 to 1011 phot./s.

Conference 8779A: Laser Acceleration of Electrons, Protons, and Ions II

Monday - Wednesday 15–17 April 2013

Part of Proceedings of SPIE Vol. 8779 Laser Acceleration of Electrons, Protons, and Ions II; and Medical Applications of Laser-Generated Beams of Particles II; and Harnessing Relativistic Plasma Waves III

8779-1, Session 1

Injection and acceleration of particles in optically shaped gas targets *(Invited Paper)*

Daniel F. Gordon, Dmitri Kaganovich, Michael H. Helle, Antonio C. Ting, U.S. Naval Research Lab. (United States)

Laser driven acceleration of electrons and ions is enhanced in gaseous targets that are formed from hydrodynamic shock waves driven in a supersonic flow. Stable injection of electrons into laser-plasma accelerators remains an important problem. In the case of gas jet targets, the colliding pulse technique has proven effective [V. Malka et al., Phys. Plasmas 16, 05603 (2009)]. However, when the plasma is formed in a structure such as a capillary or slow-flow gas cell, other techniques, such as downramp injection [e.g., K. Schmid et al., Phys. Rev. ST/AB 13, 091301 (2010)], or ionization injection [B.B. Pollock et al., Phys. Rev. Lett. 107, 045001 (2011)], may have to be considered. Downramp injection presents difficulties associated with transitioning the phase of the injected electrons, and the focusing of the laser pulse, from the injection region to the acceleration region. Ionization injection requires operation in a highly nonlinear regime, and a high degree of spatial localization of gas impurities. By using a ~0.1 joule nanosecond laser to drive a hydrodynamic shock in a supersonic gas flow, one can access a wider range of downramp injection parameters than would otherwise be possible. Experiments at NRL have shown that stable 40 MeV electrons can be produced using a 10 TW laser system. These results, and supporting simulations, will be discussed. The role of ionization in electron injection is also considered, including ab inito quantum mechanical simulations.

Optically shaped gas targets are also useful for laser acceleration of protons and ions. The most successful experiments on laser acceleration of protons in gaseous targets have made use of CO2 lasers due to the large reduction in the critical density when compared with Ti:sapphire or Nd:glass lasers. However, by driving hydrodynamic shocks in a supersonic flow, one may create an approximation of a “gas foil,” which is both dense and thin enough to allow for multi-MeV proton acceleration by a ~10 TW Ti:sapphire laser. Detailed particle-in-cell simulations of this process will be presented. The status of the corresponding experimental effort at NRL will also be discussed.

8779-2, Session 1

Numerical modeling of laser-wakefield electron acceleration to multi-GeV energies inside a dielectric capillary tube

Bhooshan S. Paradkar, Brigitte Cros, Univ. Paris-Sud 11 (France); Patrick Mora, Ecole Polytechnique (France); Gilles Maynard, Univ. Paris-Sud 11 (France)

Laser guiding inside a dielectric capillary tube [1] offers a promising approach towards achieving high quality ultra-relativistic electron beams (~ 10s of GeV) through multi-stage laser-wakefield accelerators. In this scheme, the laser, while propagating through a gas filled dielectric capillary tube, will excite linear/moderately non-linear plasma waves over a distance of several tens of Rayleigh lengths [2,3]. Each such stage will accelerate the relativistic electron beam, which will be injected at proper phase from the previous accelerator stage.

In this paper, we will present the numerical modeling of acceleration of electrons inside long capillaries (~ 10-50 cm) using the quasi-static Particle In Cell (PIC) code WAKE [4,5]. In comparison to conventional PIC codes, WAKE offers a computationally efficient and versatile platform to study such a long laser-wakefield accelerator. The code is especially useful to perform large number of parametric studies, which are necessary for the design of a multi-stage accelerator. Several modifications have been introduced into the code to model various processes relevant to the present problem such as laser guiding inside the capillary tube, injection of external relativistic electron beams into wakefields, beam loading effect of injected electron beam, laser energy loss due to ionization of gas, etc. A systematic parametric study of electron acceleration inside the capillary tube will be presented.

[1] B. Cros et al Phys. Rev. E 65, 026405 (2002)

[2] F. Wajda et al Phys. Rev. E 80, 066403 (2009)

[3] N. E. Andreev et al New Journal of Physics 12, 045024 (2010)

[4] P. Mora and T. M. Antonsen Phys. Plasmas 4, 217 (1997)

[5] P. Chessa, P. Mora and T. M. Antonsen Phys. Plasmas 5, 3451 (1998)

8779-3, Session 1

Merging conventional and laser wakefield accelerators

Benno Zeitler, Univ. Hamburg (Germany); Klaus Flöttmann, Deutsches Elektronen-Synchrotron (Germany); Tim Gehrke, Julia Grebenyuk, Florian J. Grüner, Timon Mehrling, Jens Osterhoff, Matthias Schnepp, Univ. Hamburg (Germany)

Laser wakefield accelerators deliver high quality electron beams in terms of emittance and bunch length. However there are also parameters which cannot compete with conventional machines, namely the spectral width as well as the shot to shot stability.

One reason for that is that there is no direct access to the injection mechanism of electrons into the plasma wakefield. Injecting a well-characterized electron beam produced by a conventional accelerator into a plasma wakefield could help to solve that problem: Measuring the difference in the electron spectrum in such a pump-probe type experiment should yield the possibility to directly reconstruct the field distribution.

From that point comparison with theoretical approaches as well as results from particle-in-cell codes could lead to a better understanding of the injection process.

At DESY in Hamburg there is a suited conventional accelerator for such a type of experiment, the Relativistic Electron Gun for Atomic Exploration (REGAE). We report on the status of the beamline extension at REGAE and the plans towards the external injection project with the goal to directly measure the wakefield and further improve the stability of laser wakefield accelerators. Furthermore, the outcome of that experiments could serve as a pre-study for staging of several plasma cells.

8779-4, Session 1

A high-repetition-rate laser-wakefield accelerator for studies of laser pulse propagation and electron acceleration

Zhaohan He, John A. Nees, Bixue X. Hou, Univ. of Michigan (United States); Victor Malka, Ecole Nationale Supérieure de Techniques Avancées (France); Karl M. Krushelnick, Univ. of Michigan (United States); Jérôme Faure, Ecole Nationale Supérieure de Techniques Avancées (France); Alexander G. R. Thomas, Univ. of Michigan (United States)

A high intensity laser pulse propagating in underdense plasma drives nonlinear wakefield that can be used to accelerate electrons. Relativistic electrons in the 100 MeV – 1 GeV range are produced with joule level laser systems at a low repetition rate (<< 10 Hz). By tightly focusing ultrashort laser pulses of a few millijoules, one can achieve focal intensities exceeding the relativistic threshold. Using such a low energy pulse has the benefit of a more compact system with a high repetition rate (typically kHz), which can prove useful for both practical applications and better statistical studies of laser plasma interactions.

Experiments were performed using the lambda-cubed laser at the University of Michigan - a table-top Ti:Sapphire based chirped pulse amplification (CPA) laser capable of delivering pulses with energies up to 8 mJ on target and durations of 32 fs (FWHM) at 500 Hz. The laser pulse is focused by an f/2 off-axis parabola to a 2.5 um (FWHM) spot producing a peak intensity of 3?10^18W/cm^2. Well-collimated electron beams are generated with quasi-monoenergetic spectrum peaked in the 100 keV range by acceleration in slow (non-relativistic) plasma waves on the density down-ramp of a 100 µm scale argon or helium plasma. The electrons generated from the laser-wakefield accelerator can have intrinsic short bunch durations. Hence, such 100 keV electron bunches have potential applications in ultrafast electron diffraction experiments after the linear chirping of electron beam (i.e. energy spread correlated to the longitudinal position due to propagation) is reversed. In a proof-of-principle experiment, clear static diffraction images have been obtained from a thin polycrystalline aluminum sample. A solenoid magnetic lens is used to manipulate the electron beam to improve the transverse and longitudinal coherence. The electron beam is found to be extremely stable with a pointing stability less than 400 µrad and a 14% rms shot-to-shot fluctuation in charge because of the stability and compactness of kHz laser system as well as the electron injection mechanism on the density down-ramp. The temporal phase and intensity profile of the transmitted pulse is characterized using second-harmonic-generation (SHG) frequency-resolved optical gating (FROG). The self-shortening of laser pulses down to 16~20 fs is observed with high transmittance (>90%). In addition, full 3D simulations using the particle-in-cell code OSIRIS are carried out to model the interactions.

8779-5, Session 1

Fabrication of three-dimensionally structured plasma waveguide and application to induction of electron injection and betatron oscillation in a laser wakefield electron accelerator

Yencheng Ho, Te-Sheng Hung, National Central Univ. (Taiwan); Jun-Guan Jhou, National Taiwan Univ. (Taiwan); Hamza Qayyum, Wei-Hsin Chen, National Central Univ. (Taiwan); Jiunn-Yuan Lin, National Chung Cheng Univ. (Taiwan); Hsu-Hsin Chu, National Central Univ. (Taiwan); Jyhpyng Wang, National Taiwan Univ. and Academia Sinica (Taiwan); Szu-Yuan Chen, National Central Univ. and Academia Sinica (Taiwan)

By adding a transverse heater pulse with controlled intensity distribution into the axicon ignitor-heater scheme for optically producing a plasma waveguide, three-dimensionally structured plasma waveguide can be fabricated. This enables integration of the many functional stages of each particular application in a single gas jet and optimization of each stage. The additional heater pulse incident from the direction perpendicular to the propagation axis of the axicon pulses is line-focused onto the gas jet and spatially overlaps the axicon pulses to generate further heating of the plasma filament produced by the axicon pulses in a spatially and temporally controlled manner. The succeeding evolution of the plasma leads to a properly structured plasma waveguide that suits for targeted application. With this technique, induction of electron injection in a plasma-waveguide-based laser wakefield accelerator was achieved and resulted in production of a quasi-monoenergetic electron beam with an electron energy reaching 280 MeV and an energy spread as low as 1% in a 4-mm-long gas jet. The correlation between the variations of guided longitudinal probe beam profile and injection probability of the quasi-monoenergetic electron beam with change of the transverse heater delay suggests that the creation of a section in the plasma waveguide with an elliptical cross-section, resulting from the retarded arrival of the transverse heater with respect to the axicon heater, led to electron injection. It is believed that the expansion of the pump pulse beam size and therefore the driven plasma bubble in the horizontal plane resulted in transverse wave-breaking and thus injection of electrons. Furthermore, strong hard X-ray beam was also observed upon further increase of transverse heater delay. It is proposed that under such condition the heating of the plasma filament on the incident side of the transverse heater is higher than that on the opposite side, as a result of significant inverse bremsstrahlung absorption of the transverse heater by the plasma. This leads to a horizontally asymmetric expansion of plasma and thus the center of the waveguide in the irradiated section is shifted horizontally, followed by a corresponding shift in the guided pump laser pulse and thus the driven plasma bubble. During this period the electron bunch in the bubble experiences a transverse kick due to attraction from the ions, gaining a large transverse momentum, and therefore betatron oscillation ensues after the laser pulse resumes its original path. Following these models, simultaneous implementation of two independently shaped transverse heater beams for optimizing electron injection and betatron oscillation respectively are undergoing.

8779-6, Session 2

Self-injection and stability in laser-plasma accelerators *(Invited Paper)*

Cédric Thaury, Ecole Polytechnique (France); Sebastien Corde, Ecole Polytechnique (France) and SLAC National Accelerator Lab. (United States); Kim Ta Phuoc, Ecole Nationale Supérieure de Techniques Avancées (France); Agustin Lifschitz, Remi Lehe, Guillaume Lambert, Ecole Polytechnique (France); Antoine Rousse, Victor Malka, Ecole Nationale Supérieure de Techniques Avancées (France)

Laser-plasma accelerators can produce high quality electron beams, up to giga-electronvolts energy, from a centimeter length plasma. The accelerated electron beams have properties (charge, peak current, energy spread, emittance) that are comparable to those obtained on medium-size conventional installations. Despite these qualities and increasing shot to shot stability, their reliability still prevents laser plasma accelerators from being a serious alternative to conventional accelerators.

Here we show that transverse self-injection is an important source of instability. Both experimental and numerical results actually indicate that this injection mechanism strongly depends on the shape of the laser focal spot. Since the focal spot slightly changes shot-to-shot, transverse injection is intrinsically unstable. In contrast, we show that another self-injection mechanism, namely longitudinal injection, is much less sensitive to the shape of the focal spot and leads therefore to a much better stability.

Both injection mechanisms are studied experimentally using a gas cell with an adjustable length. The results demonstrate that, at high electron density, longitudinal and transverse injections sequentially occur, whereas only longitudinal injection occurs at lower density. The properties of the electron beams injected by each mechanism are studied in details. The analysis of the angular profiles of the X-ray betatron emission demonstrates that the transverse properties of the accelerated electrons are much more stable for longitudinal injection than for transverse injection. In addition, longitudinal injection is observed to lead to a 100% probability of injection of quasi-monoenergetic electron beams with a 3% RMS stability in peak energy and an emittance smaller than 1 pi.mm.mrad.

8779-7, Session 2

Electron injection and emittance control in laser-plasma accelerators

Eric Esarey, Carl B. Schroeder, Min Chen, Cameron GR Geddes, Stepan S. Bulanov, Carlo Benedetti, Lule Yu, Sergey Rykovanov, Wim P. Leemans, Lawrence Berkeley National Lab (United States)

Electron injection methods are analyzed in an effort to minimize the emittance in laser-plasma accelerators. Methods considered include two-color colliding pulse injection, ionization injection, and a combination of these approaches. By utilizing a colliding pulse injection method in which the colliding pulses have different frequencies, the beat wave phase velocity can be tuned. Appropriately choosing the frequencies can reduce the injection threshold and optimize the bunch parameters. Ionization injection using a single pulse is analyzed, and the relatively large emittances that are produced are a result of the residual transverse momentum from electrons being born in an intense, transversely polarized laser field. By using

transverse propagating colliding pulses, electron injection and transverse emittance can be controlled. For transverse pulses with equal frequencies, a beam with extremely small emittance is obtained by placing the transverse standing wave position close to the density peak of the wake, which results in trapping in the subsequent wake bucket. Ionization can increase the transverse injection area and the final injection charge. Simulations show transverse momentum spread can be as small as 0.04mc, which is over an order of magnitude smaller than typical laser injection schemes. For transverse pulses with different frequencies, transverse beat waves can be used to generate asymmetric injection, which can increase betatron radiation emission. Other ionization injection schemes that use multiple pulses are also examined. Supported by the U.S. Department of Energy.

8779-8, Session 2

Controlled magnetic self-injection and electron acceleration towards the energy frontier

Jorge M. Vieira, Vishwa B. Pathak, Joana L. Martins, Ricardo A. Fonseca, Univ. Técnica de Lisboa (Portugal); Warren B. Mori, Univ. of California, Los Angeles (United States); Luis O. Silva, Univ. Técnica de Lisboa (Portugal)

Quasi-mono energetic electron bunches are currently produced in state-of-the-art laser wakefield acceleration experiments. The next challenge in this technology is to control the generation of electrons with properties suitable for several applications, including medical, scientific, and industrial applications. In addition, higher electron energies are also required for high energy physics purposes. To this end, several controlled injection techniques have been developed. These make use of couter propagating lasers, ionization mechanisms, or plasma ramps to control the energy and charge of self-injected electrons. However, the control of the transverse self-trapping, of relevance for radiation generation, has been little explored. In this talk, a novel controlled injection mechanism that resorts to external, uniform magnetic fields to relax the trapping thresholds will be described. An analytical model is developed showing that the direction and amplitude of the magnetic field control the transverse location and trapping cross-sections. In addition, the trapped charge can be controlled by manipulating the magnetic field amplitude and spatial extent. Multi-dimensional simulations confirm our analytical findings, and show that this scheme can be used to generate high quality electron bunches in both laser and plasma wakefield acceleration with potential for radiation generation close to the undulator regime. Additional simulations in boosted frames also show the possibility to accelerate electrons to 10-100 GeVs in plasma based accelerators using next generation lasers systems.

8779-9, Session 2

Laser-plasma accelerated electron beams as drivers for free-electron lasers

Carl B. Schroeder, Eric Esarey, Jeroen van Tilborg, Lawrence Berkeley National Lab. (United States); Zhirong Huang, Yuantao Ding, SLAC National Accelerator Lab. (United States); Andreas Maier, Florian J. Grüner, DESY (Germany); Wim Leemans, Lawrence Berkeley National Lab. (United States)

Laser-plasma accelerators are able to produce ultra-high accelerating fields, enabling compact accelerators, and ultra-short (fs) beams with high-peak currents. The 6D beam brightness of a laser-plasma accelerated beam is comparable to state-of-the-art conventional electron beam sources, although the projected energy spread hinders application to free-electron lasers (FELs). Beam slippage in the free-electron laser also suppresses lasing in the soft-x-ray, and longer, wavelength regimes. Given present experimentally achievable laser-plasma accelerator electron beam parameters, we discuss several possible methods of phase space manipulation after the laser-plasma accelerator to achieve FEL lasing. Beam decompression is examined as a solution to reduce the slice energy spread and slippage effects. Beam dispersion, coupled to a transverse gradient undulator, is also considered to enable FEL application of the laser-plasma accelerated beams.

8779-10, Session 3

Theoretical studies of collisionless shocks for laser-acceleration of ions *(Invited Paper)*

Anne Stockem, Univ. Técnica de Lisboa (Portugal); Frederico Fiuza, Lawrence Livermore National Lab. (United States); Elisabetta Boella, Univ. Técnica de Lisboa (Portugal); Ricardo A. Fonseca, Univ. Técnica de Lisboa (Portugal) and Univ. de Lisboa (Portugal); Luis O. Silva, Univ. Técnica de Lisboa (Portugal); Chandrashekhar J. Joshi, Warren B. Mori, Univ. of California, Los Angeles (United States)

Recently, strong effort has been done in exploring shock acceleration for the generation of highly energetic ion beams, with applications e.g. for medical purposes. The heating of a near-critical density plasma target with a laser, increases the electron temperature and excites ion acoustic waves, which can lead to electrostatic shock formation due to non-linear wave breaking. The higher inertia background ions are reflected and accelerated at the shock potential, showing a quasi-monoenergetic profile. For the first time, its feasibility has been demonstrated experimentally, gaining 20 MeV protons with a very narrow energy spread [1] and a predicted scaling up to 200 MeV for lasers with a0 = 10 [2]. In the quest for high proton energies, optimal conditions for shock formation have to be found. We developed a relativistic model that connects the initial parameters with the steady state shock Mach number, which is based on the Sagdeev approach [3,4], showing an increase of the ion energy for high upstream electron temperatures and low downstream to upstream density ratios [5] and high temperature ratios, which has been confirmed by particle-in-cell simulations. In the context of producing a quasi-monoenergetic beam profile, we studied the enhancement of the Weibel instability in an electrostatic shock setup. Governing parameter regimes for the transition to an electromagnetic shock, which is associated with a broadening of the ion spectrum, were determined analytically and confirmed with simulations.

[1] D. Haberberger, S. Tochitsky, F. Fiuza, C. Gong, R.A. Fonseca, L.O. Silva, W.B. Mori & C. Joshi, Nature Physics 8, 95 (2012).

[2] F. Fiuza, A. Stockem, E. Boella, R.A. Fonseca, L.O. Silva, D. Haberberger, S. Tochitsky, C. Gong, W.B. Mori & C. Joshi, Phys. Rev. Lett., accepted (2012), ArXiv1206.2903F.

[3] R.Z. Sagdeev, Review of Plasma Physics, vol. 4 (Consultans Bureau, 1966).

[4] G. Sorasio, M. Marti, R.A. Fonseca & L.O. Silva, Phys. Rev. Lett. 96, 045005 (2006).

[5] A. Stockem, F. Fiuza, E. Boella, R.A. Fonseca & L.O. Silva, in prep.

8779-11, Session 3

Onset of relativistically induced transparency in the radiation pressure acceleration regime of intense laser-foil interactions

Paul McKenna, Ross J. Gray, David C. Carroll, Univ. of Strathclyde (United Kingdom); Chris Murphy, The Univ. of Edinburgh (United Kingdom); Haydn Powell, David MacLellan, Graeme Scott, Univ. of Strathclyde (United Kingdom); Chris Brady, The Univ. of Warwick (United Kingdom); Chris Ridgers, Univ. of Oxford (United Kingdom); Nicola Booth, Robert J. Clarke, David Neely, Rutherford Appleton Lab. (United Kingdom)

In recent years a novel mechanism for ion acceleration based on laser radiation pressure (radiation pressure acceleration, RPA), has emerged as a favourable scheme for the production of high flux, high energy and low energy-spread beams of ions. The Light-Sail mode of RPA, which occurs with ultrathin targets, is predicted to be yield the high energy ions. In the ultraintense laser and ultathin target parameter spaces in which Light-Sail RPA is predicted to dominate a balance must be achieved where the target is thin enough and the laser high enough in intensity to efficiency accelerate ions, but not so high in intensity as to

burn through the target before significant acceleration takes place.

We report on results from a recent experimental campaign, using the Astra-Gemini laser at the Rutherford Appleton Laboratory, in which the onset of induced transparency is investigated in the parameter space for Light-Sail RPA. The results show the onset of transparency with linearly polarised laser light above a certain intensity threshold, whereas RPA is achieved at the same intensity with circularly polarised light. Coupled 2D PIC simulations are in good agreement with the experimental results.

8779-12, Session 3

Transition of proton energy scaling driven by petawatt-laser-plasma interactions

I Jong Kim, Ki Hong Pae, Chul Min Kim, Hyung Taek Kim, Il Woo Choi, Jae Hee Sung, Seong Ku Lee, Tae Jun Yu, Peter V. Nickles, Tae Moon Jeong, Jongmin Lee, Gwangju Institute of Science and Technology (Korea, Republic of)

The particle acceleration using Petawatt (PW) Ti:sapphire laser pulses is one of the most attractive research in the relativistic laser-plasma interactions. We report here a laser-driven high energy proton beam created in the interaction of a PW Ti:sapphire laser pulse (30fs, 30J CPA Ti:sapphire laser system (PULSER I) installed at APRI, GIST) which is important step to proton/ion therapy. Double plasma mirror was installed to achieve ultrahigh contrast (10^-11 at 6 ps before the main laser pulse) laser pulse before entering the target. By irradiating laser pulses on ultrathin polymer targets in the intensity range from 0.5?10^20 W/cm^2 to 3.3?10^20 W/cm^2, high energy proton beams were measured using Thomson parabola spectrometer. The maximum proton energy with 45 MeV was obtained from a 10-nm thick polymer target (F8BT) by irradiating linearly-polarized laser pulses with an intensity of 3.3?10^20 W/cm^2. For thicker targets than 50 nm, the proton acceleration was dominated by thermal electrons in the overall intensity range. On the other hand, for thinner targets than 50 nm, the proton acceleration was mainly dominated by coherent electrons in the higher intensity than ~ 2?10^20 W/cm^2. These experimental results represent that firstly we have realized the transition of proton energy scaling from square-root scaling (~I^1/2) to linear scaling (~I^1) which is dominated by TNSA-like thermal electrons and RPA-like coherent electrons respectively. And several interesting features, such as electron temperature, and quasi-monoenergetic proton/ions that can discriminate the thermal-electron and coherent-electron acceleration were obtained. In order to explain the experimental results, we performed 2D and 3D particle-in-cell simulations. From this, we have found the transitions of proton acceleration mechanism such as TNSA-like, RPA-like, and hybrid acceleration as the laser intensity increases. The linear scaling of proton acceleration approaches to ~200 MeV proton energy which competes against accelerator based proton therapy when the laser intensity increases to 1.5?10^21 W/cm^2 by applying short focal length optics.

8779-13, Session 3

Prompt pre-thermal laser ion sheath acceleration with ultra-short laser pulses

Karl Zeil, Josefine Metzkes, Thomas Kluge, Michael Bussmann, Thomas E. Cowan, Stephan D. Kraft, Ulrich Schramm, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

High-intensity laser-plasma ion generation is promising as a compact, low-cost proton source for applications like ion beam therapy. Using a femtosecond table-top laser system, we study the intra-pulse phase of the laser driven proton acceleration and show that protons efficiently gain energy in these early times [1].

In recent laser-ion acceleration experiments performed at the 150 TW Draco laser in Dresden, Germany, we have demonstrated the importance of a precise understanding of the electron dynamics in solids on an ultra-short time scale. For example, with ultra-short laser pulses a description based purely on the evolution of a thermal electron ensemble, as in standard TNSA models, is not sufficient anymore. Rather, non-thermal effects during the ultra-short intra-pulse phase of laser-electron interaction in solids become important for the acceleration of ions when the laser pulse duration is in the order of only a few 10 femtoseconds. While the established maximum ion energy scaling in the TNSA regime goes with the square root of the laser intensity, for such ultra short pulse durations the maximum ion energy is found to scale linear with laser intensity [2], motivating the interest in such laser systems.

Investigating the influence of laser pulse contrast, laser polarization and laser incidence angle on the proton maximum energy and angular distribution, we present recent advances in the description of the laser interaction with solids, focusing on the implications of intra-pulse non-thermal phenomena on the ion acceleration.

References

1. K. Zeil, J. Metzkes, T. Kluge, M. Bussmann, T.E. Cowan, S. D. Kraft, R. Sauerbrey and U. Schramm, Direct observation of prompt pre-thermal laser ion sheath acceleration, Nature Communications 3 (874), 2012

2. K. Zeil, S. D. Kraft, S. Bock, M. Bussmann, T.E. Cowan, T. Kluge, J. Metzkes, T. Richter, R. Sauerbrey and U. Schramm, Scaling of proton energies in ultrashort pulse laser plasma acceleration, New Journal of Physics 12 (045015), 2010

8779-14, Session 4

Generation of 50-MeV/u He ions in laser-driven ion acceleration with cluster-gas targets *(Invited Paper)*

Yuji Fukuda, Hironao Sakaki, Masato Kanasaki, Akifumi Yogo, Satoshi Jinno, Motonobu Tampo, Anatoly Y. Faenov, Tatiana A. Pikuz, Yukio Hayashi, Masaki Kando, Alexander S. Pirozhkov, Takuya Shimomura, Hiromitsu Kirayama, Satoshi Kurashima, Tomihiro Kamiya, Japan Atomic Energy Agency (Japan); Keiji Oda, Tomoya Yamauchi, Kobe Univ. (Japan); Kiminori Kondo, Sergei Bulanov, Japan Atomic Energy Agency (Japan)

In laser-driven ion accelerations, diagnosis of laser-accelerated ion beams attracts much attention and a precise characterization of accelerated ions is a crucial issue to develop a compact laser ion accelerator for medical and industrial applications. Solid state nuclear track detectors such as CR-39 detectors have been so far extensively used to detect laser-accelerated ions [1]. It is, however, impossible to detect ions with energies higher than the detection threshold limit of the CR-39, where the detection threshold limit is defined as the particle energy where the stopping power in the detector becomes smaller than the sensitivity of the detector. For example, in the case of BRYOTRAK (Fukuvi Chemical Industry, Japan), it cannot detect He ions having energies of 10 MeV per nucleon and more.

Therefore, new methods to detect ions whose energies are far beyond the detection threshold limit of the CR-39 are required to further facilitate the laser ion acceleration experiments. Here we demonstrate a new simple diagnosis method for high energy ions utilizing a single CR-39 detector mounted on plastic plates to identify the presence of the high energy component beyond the detection threshold limit of the CR-39 [2]. In addition, we have applied this method to the laser-driven ion acceleration experiments using cluster-gas targets [3].

The proof-of-principle experiments for the new ion detection method were carried out at TIARA facility in JAEA-TAKASAKI, which delivered 4^He^2+ ion beam with an energy of 100 MeV (25 MeV per nucleon). In contrast to the fact that the stopping power of the incident ion beam is too small to create etchable tracks in the 100-um thick CR-39, a number of etch pits having elliptical openings were created on the rear surface of the CR-39. The growth curve analyses using the multi-step etching technique revealed the following scenario: The incident He ions once passed through the CR-39 without creating any etchable track, and various nuclear reactions such as nuclear spallation were induced by incident He ions in the plastic plates. As a result, the backscattered He and other heavy ions hit into the CR-39 from the rear surface and created the etchable tracks on the rear surface [2].

This method in combination with a magnetic energy spectrometer was applied to the laser-driven ion acceleration experiments using the cluster-gas target, which consists of submicron-size CO_2 clusters and a background He gas, at J-KAREN laser facility in JAEA-KPSI. On the rear surface, a number of etch pits having elliptical openings were observed to demonstrate that laser-accelerated ions with energies up

to 50 MeV per nucleon were generated at a laser intensity of 7?10^18 W/cm^2 (40 fs, 1 J pulses) [3].

In addition to the above result, recent results on ion acceleration researches using cluster-gas targets at JAEA-KPSI will be presented.

[1] Y. Fukuda et al., Phys. Rev. Lett. 103,165002 (2009).

[2] M. Kanasaki et al., Jpn. J. Appl. Phys. 51, 056401 (2012).

[3] Y. Fukuda et al., Radiat. Meas. in press (2012).

8779-15, Session 4

Laser ion acceleration with low density targets: a new path towards high intensity, high energy ion beams *(Invited Paper)*

Marc Glesser, Ecole Polytechnique (France)

Intense research is being conducted on sources of laser-accelerated ions and their applications [1,2]. Experiments on the low density regime of laser ion acceleration [3] were performed at LULI in may 2011. In this regime, volume effects are expected to dominate, while for solid foils, ion acceleration is directly related to the electron surface density and the number of accelerated ions is limited. Simulations therefore show that it is possible to reach high ion energies with a high number of accelerated ions and a high conversion efficiency [4]. This scheme also leads to less debris than solid foils and is more adapted to high repetition lasers. Very promising results were obtained at LULI considering the laser energy involved (~5J). A first ns pulse was focused on a thin target to explode it and a second laser with a pulse duration of 350 fs and a high intensity was focused on the exploded foil. The delay between two lasers allowed to control the density gradient seen by the second laser pulse. The transition between various laser ion acceleration regimes depending on the density gradient length was studied and protons with energies close to the energies of TNSA accelerated protons were obtained for various exploded foils configurations. Interferometry diagnostics coupled to measurements of the ion spectra at various angles behind the targets and compared with 2D hydrodynamical and Particle-In-Cell simulations allowed to illustrate recent theoretical results. As this regime scales well with laser energy, new experiments were performed in 2012 with more laser energy (~180J) on the LLNL Titan laser. A secondary long pulse laser was again used to control the density profile of the target. In this high energy regime, protons with energies significantly higher than the ones of TNSA accelerated protons were obtained when exploding the foil while keeping a good beam quality. These results demonstrate that low-density targets is a promising candidate for an efficient proton source. This source can be optimized by choosing appropriate plasma conditions.

References

[1] M. Borghesi et al., Fusion Sci. Technol. 49, 412 (2006)

[2] J. Fuchs et al., C. R.Physique 10, 176-187 (2009)

[3] L. Willingale et al., Phys. Rev. Lett. 96, 245002 (2006); C. Palmer et al., Phys. Rev. Lett. 106, 014801 (2011); D. Harberger et al., Nature Physics 8, 95 (2012)

[4] T. ZH. Esirkepov et al., JETP Lett. 70, 82 (1999); M. Yamagiwa et al., Phys Rev. E 60, 5987 (1999); Y. Sentoku et al, Phys, Rev. E 62, 7271 (2000), E. d'Humières et al., J. Phys.: Conf. Ser. 244, 042023 (2010)

8779-16, Session 4

Simulation studies of radiation-pressure driven light sail and shock acceleration

Andrea Sgattoni, Politecnico di Milano (Italy) and National Institute of Optics (Italy); Andrea Macchi, Univ. di Pisa (Italy); Tatyana V. Liseykina, Univ. Rostock (Germany); Amritpal S. Nindrayog, Univ. di Pisa (Italy) and National Institute of Optics (Italy); Matteo Tamburini, Max-Planck-Institut für Kernphysik (Germany) and National Institute of Optics (Italy); Francesco Pegoraro, Univ. di Pisa (Italy) and National Institute of Optics (Italy)

Simulation results are reported for two ion acceleration mechanisms driven by radiation pressure. Three-dimensional (3D) simulations of the acceleration of thin foils by circularly polarized pulses ("light sail" regime) at ultra-relativistic intensities (a0>100) show an ion energy that is higher than observed in 1D and 2D simulations, presumably due to density rarefaction and self-wrapping of the laser pulse as the foil is deformed. Radiation friction and anisotropy effects are negligible for circular polarization but relevant for linear polarization. Simulations of the interaction of linearly polarized pulses with long-scalelength, moderately overdense plasmas at mildly relativistic intensities (a0=1--10) show radiation-pressure driven formation of both solitary and shock waves leading to ion acceleration in the target bulk. In 1D simulations, the spectrum of the accelerated ions is monoenergetic within some range of the initial ion temperature. In 2D simulations, the onset of rippling at the shock surface apparently leads to broadening of the energy spectrum.

8779-17, Session 4

Evanescent-wave proton accelerator driven by intense THz pulses

Laszlo Palfalvi, Univ. of Pécs (Hungary); József A. Fülöp, MTA-PTE High-Field Terahertz Research Group (Hungary) and ELI-ALPS (Hungary); György Tóth, Univ. of Pécs (Hungary); János Hebling, Univ. of Pécs (Hungary) and MTA-PTE High-Field Terahertz Research Group (Hungary)

Hadron therapy requires particle beams having ~100 MeV/nucleon energy, and relative energy fluctuation below 1% (U. Linz et. al., Phys. Rev. ST Accel. Beams 10, 094801 (2007)). Laser-driven accelerators produce ion beams with only tens of MeV/nucleon energy, and extremely wide spectra (R.A. Snavely et. al., Phys. Rev. Lett. 85, 2945 (2000), J. Fuchs et. al., Nature Physics 2, 48 (2006)). The highest so far proton energy reported from a laser-driven proton accelerator with solid target is 58 MeV (R.A. Snavely et. al., Phys. Rev. Lett. 85, 2945 (2000)), which is the maximum value of an extremely broad energy spectrum.

Here, a compact solution is proposed for post-acceleration and monochromatization of particles leaving the laser-driven accelerator. The proposed method uses for acceleration the evanescent field of an intense THz pulse undergoing total internal reflection at a dielectric-vacuum interface. In order to minimize the transversal deflecting forces the evanescent accelerating field between a symmetrically irradiated dielectric crystal pair (B.R. Fradsen et. al., Laser Physics 16, 1311 (2006)) was used. It is shown by calculations that THz pulses are promising for this application, due to their advantageous wavelength, and to the fact that they can be generated with extremely high electric field strength. Applying tilted-pulse-front pumping highly nonlinear materials, such as LiNbO3, became available for efficient optical rectification of femtosecond laser pulses (J. Hebling et. al., Optics Express 10, 1161 (2002)). Since then, this technique has been providing the highest (125 mJ) THz pulse energies (J.A. Fülöp et. al., Opt. Lett. 37, 557 (2012)) and highest electric field strengths (> 1 MV/cm) (H. Hirori et. al., Appl. Phys. Lett. 98, 091106 (2011)) ever achieved with table-top sources around 1 THz frequency.

Analytical formulae were given for the phase velocity of the evanescent THz field – that can be set by the geometry - in order to extract the maximal energy gain from a THz pulse. Using THz pulses with electric field strength in the MV/cm range in case of a proton having 40 MeV initial energy 2-3 MeV gain can be reached in cm range acceleration length. By sequential use of such accelerator units the proton energy can be increased from 40 to 100 MeV in ~10 stages. As an important result it was shown by numerical calculations that with this setup, besides acceleration, the energy bandwidth of a proton bunch can be decreased from 10% below 1%. The proposed method holds promise to contribute to the realization of compact and flexible, entirely laser-based proton accelerators suitable for hadron therapy.

8779-18, Session 5

Laser-accelerated ion pulses for high dose-rate applications *(Invited Paper)*

Jörg Schreiber, Ludwig-Maximilians-Univ. München (Germany)

After more than one decade of successful operation at the Max Planck Institute for Quantum Optics, the Advanced Titanium-Sapphire Laser (ATLAS) system has been dismantled and is currently transferred to its new, temporary home, the Laboratory for Extreme Photonics (LEX). This move will allow us to upgrade the peak power from currently 60 TW to 300 TW before it can take on its final upgrade to 3 PW at the Centre for Advanced Laser Applications (CALA), possibly constituting one of the world's most powerful laser systems. The opportunities are manifold; GeV-electron bunches with a few femtosecond pulse duration will be available routinely and in turn enable for the generation of even shorter light, UV, X- and Gamma-ray pulses. The high laser pulse energy (60J) paired with the short duration (20fs) will allow to access light intensities of up to 1023W/cm2 and address fundamental questions of physics.

One major prospect is the generation of ion bunches with energies beyond 100 MeV/u, sufficiently high to approach and investigate their applicability in tumour therapy. At present, the application of nanometer thin foils seems to be most promising both in terms of achieving highest energy and conversion efficiency of laser energy to usable ion energy. The demands on the quality and control of the laser pulses, mainly in terms of the suppression of pre-pulses, are enormous. Despite of these difficulties, we could demonstrate first biological studies with tumour cells irradiated by laser accelerated proton bunches with single shot doses of several Gray delivered within 1 nanosecond. This demonstration has been a major mile stone of our research. Moreover, the combined efforts in laser, target and detector development disclosed a number of new and partially surprising insights that constitute my excitement for this field of physics and motivate for the future challenges and possibilities that await us.

8779-19, Session 5

Electron temperature scaling in laser interaction with solids

Thomas Kluge, Thomas E. Cowan, Alexander Debus, Ulrich Schramm, Karl Zeil, Michael Bussmann, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

A precise knowledge of the temperature and number of hot electrons generated in the interaction of short-pulse high-intensity lasers with solids is crucial for harnessing the energy of a laser pulse in applications such as laser-driven ion acceleration or fast ignition.

We present a novel approach to model the average of the kinetic energy of an ensemble of electrons which is based on a weighted average of the energy of a single, adiabatically accelerated electron.

We find that a Lorentz-invariant average over the eigenzeit of such a model electron gives proper results with respect to simulations and experiments.

This averaging corresponds to a non-homogeneous distribution in laboratory time of electrons injected into the plasma. From simulations it can be derived that the weighting function in many interesting cases is proportional to the inverse of the energy, which is in agreement with the average over eigenzeit. The thus derived temperature scaling is in perfect agreement with simulation results and clearly follows the trend seen in recent experiments, especially at high laser intensities where other scalings fail to describe the simulations accurately.

8779-20, Session 5

Laser plasma proton acceleration experiments using foam-covered and grating targets

Andrea Sgattoni, Politecnico di Milano (Italy) and National Institute of Optics (Italy); Tiberio Ceccotti, Vincent Floquet, Commissariat à l'Énergie Atomique (France); Alessandro Zani, Politecnico di Milano (Italy); Ondrej Klimo, Czech Technical Univ. in Prague (Czech Republic); Andrea Macchi, Univ. di Pisa (Italy); Matteo Passoni, Politecnico di Milano (Italy)

Experimental results are reported for two different configurations of laser driven ion acceleration using solid targets with a structured layer on the irradiated side. Two experimental campaigns have been performed exploiting the 100TW 25fs Ti:Sa UHI-100 laser pulse at CEA Saclay. The use of a double plasma mirror allowed a contrast ratio of >1e9 so that the structures of the front surface withstood the prepulse.

"Foam" targets have been manufactured by depositing a 10 micron nanostructured carbon foam with an average density of 1-5mg/cm3 on a ~1 micron thick aluminium foil. At maximum focalization, corresponding to an intensity of 1e19 W/cm2. the foam targets gave a maximum proton energy similar to the case of bare aluminium target (about 6 MeV). Reducing the intensity by moving the target from the best focus plane, the presence of the foam enhanced the maximum proton energy, obtaining about 1.5MeV vs. 500KeV with a target 500 micron from the best focus, corresponding to an intensity of 5e16 W/cm2.

"Grating" targets have been manufactured by engraving thin mylar foils (0.9, 20 and 40 micron) with a regular modulation having 1.6 micron period and 0.5 micron depth. The periodicity of the grating corresponds to a resonant incident angle of 30 degrees for the excitation of surface waves.

Considering a target of 20 micron and changing the angle of incidence from 10 to 45 degrees, a broad maximum in the proton energy cut-off was observed around the resonant angle. The proton energy cut-off was up to 5 MeV for a laser intensity of 1e19 W/cm2. As suggested by numerical simulation, radiochromic films placed 300 degrees around the target showed a very intense electron signal suggesting the presence of a peak emission tangent to the target only in presence of the grating.

The experiments have been supported by the LaserLAB EU access scheme.

8779-21, Session 5

Energetic negative ion and neutral atom beam generation at passage of laser accelerated high energy positive ions through a liquid spray

Sargis Ter-Avetisyan, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

The talk will present the experimental demonstration of energetic negative ion and neutral atom beam generation in water spray target consist of sub-micron size droplets.

The approach employed is completely novel and very different from those used in existing negative ion source technology. The interaction of energetic positive ion beam with liquid spray produces copious energetic negative ion and neutral atom beams of different species (C-, O- and H-) with characteristics similar to positive ion beam.

For laser accelerated high-energy ion beams major applicative prospects come from their unique characteristics: high-brightness, and ultralow-emittance. Our method is highly benefiting from all these properties and, additionally, from the broad energy spectrum of these ions. It allows studying the variety of collisional processes: to measure their cross sections and in a vide energy range.

Negative ions are employed in many processing applications and in the accelerator technology; including heating of tokamak plasmas and the next generation of accelerators: spallation sources. Additionally, negative ions can be an alternative to positive ions for heavy ion fusion drivers because the electron accumulation would be prevented and, if desired, the beams could be photo detached to neutrals. These applications are demanding high brightness negative ion beams.

In our experiments 10^9 negative ions per steradian in 5% energy bandwidth have been generated. To our knowledge this is by far the brightest negative ion source reported (10^8A•cm^-2sr^-1). The observation opens new possibilities for creation of efficient and compact sources of energetic different negative ion species and neutral atoms.

8779-22, Session 5

Ultra-intense laser neutron generation through efficient deuteron acceleration

Calvin A. Zulick, Univ. of Michigan (United States)

Fast neutrons (>1 MeV) have important applications in biological imaging, materials testing, and active interrogation for homeland security. The generation of fast neutrons through ultra-intense laser plasma interactions is an alternative to conventional acceleration schemes which offers the potential for compact accelerators through the higher electric potentials possible in plasmas.

Experiments at the HERUCLES laser facility have been performed to investigate Li(d,n)Be reactions at an average on-target intensity of 1 x 10^21 W/cm^2. The neutrons were produced in a two-stage pitcher-catcher configuration by accelerating deuterons into bulk LiF. Cryogenically cooled aluminum thin films (800 nm) were used as a substrate for a heavy water (D20) ice layer which resulted in a nearly pure deuteron acceleration, with deuterons comprising over 99% of the accelerated hydrogen. Deuterons were primarily accelerated by Target-Normal-Sheath-Acceleration with an exponential energy spectrum and a cut-off energy of 6 MeV. The neutron yield was measured to be up to 1 (+/- 1.4) x 10^7 neutrons/sr with energies up to 15 MeV. Particle-in-cell and Monte-Carlo simulations have been performed to model the experimental deuteron and neutron spectra. Sublimation of the ice layer has been shown to influence the deuteron spectra through the introduction of a rear surface density gradient. The observed neutron spectra exhibited two peaks which were shown to be a combination of direct (En = Ed + Q) and proton stripping reactions (En = Ed/2).

8779-23, Session 6

Small-scale laser based electron accelerators for biology and medicine: a comparative study of the biological effectiveness *(Invited Paper)*

Luca Labate, Istituto Nazionale di Ottica (Italy) and Instituto Nazionale di Fisica Nucleare (Italy); Maria Grazia Andreassi, Consiglio Nazionale delle Ricerche (Italy); Federica Baffigi, Istituto Nazionale di Ottica (Italy); Giuseppina Basta, Ranieri Bizzarri, Andrea Borghini, Giuliana Candiano, Carlo Casarino, Consiglio Nazionale delle Ricerche (Italy); Fabio Di Martino, Azienda Ospedalier Univ. Pisana (Italy); Lorenzo Fulgentini, Istituto Nazionale di Ottica (Italy); Maria Carla Gilardi, Consiglio Nazionale delle Ricerche (Italy); Antonio Giulietti, Istituto Nazionale di Ottica (Italy); Francesco Lenci, Giorgio Russo, Antonella Sgarbossa, Consiglio Nazionale delle Ricerche (Italy); Claudio Traino, Azienda Ospedaliero-Univ. Pisana (Italy); Leonida A. Gizzi, Istituto Nazionale di Ottica (Italy) and Istituto Nazionale di Fisica Nucleare (Italy)

Electron accelerators relying on the Laser WakeField Acceleration mechanism in plasmas are now entering a mature phase, allowing them to be considered as reliable alternatives to the RF LINACs used in medical practice such as, for instance, radiotherapy. As a matter of fact, electron accelerators based upon ultrashort and ultraintense table-top lasers exhibit a wealth of advantages when compared to conventional accelerators in terms, for instance, of radioprotection requirements, operation reliability and flexibility and so on. Furthermore, due to the intrinsic accelerating fields being much larger than those achievable with RF LINACs, electron bunches with energies up to a few tens or even hundreds of MeV would be easily achievable, thus representing a new option in radiotherapy and other medical practices.

As of today, the figures of the electron bunches delivered by small-scale laser based accelerators are comparable to the ones produced by conventional LINACs as for electron energy, total charge, average current and delivered dose, etc. However, due to the ultrashort bunch duration (of the order of a few up to a few tens of femtoseconds), the peak current is much higher (typically, up to six orders of magnitude) than in conventional LINACs. From one side, this opens up a wealth of potential new studies and applications, involving possible unexplored biological responses to such high electron currents. On the other hand, this demands accurate studies at a pre-clinical stage before even considering laser-driven accelerators for an actual medical use. The group operating at the Intense Laser Irradiation Laboratory of the CNR in Pisa is currently pursuing a 3-years project aimed at sudying the biological response to electrons from laser-driven accelerators. The project gathers together people with multidisciplinary expertises (namely, physics, medicine and biology). As a starting point, different human cells (namely, human lymphocytes and fibroblasts) have been irradiated using laser-accelerated electrons at low energy (up to a few MeV) and the induced biological effects in terms of cell alteration and survival have been studied by means of well-established biological techniques (MN assay, scoring of gamma-H2AX, etc.). The delivered dose was studied by combining experimental measurements and Monte Carlo (GEANT4 based) simulations. The biological response was compared to the one induced with electrons produced by a conventional LINACs used for Intra-Operatory Radiotherapy and/or to previous results obtained with LINACs found in the literature. A discussion of the experimental issues and the obtained results will be given together with an overview of the planned activity for the next few years.

8779-24, Session 6

Controlled injection in a wakefield accelerator using colliding laser pulses and plasma density gradients *(Invited Paper)*

Olle Lundh, Lund Univ. (Sweden)

The injection of quasimonoenergetic electron beams into a laser wakefield accelerator is demonstrated experimentally using density gradients at the edges of a plasma channel. Two methods are explored for plasma channel generation using: i) a thin wire partially obstructing the flow and creating shockwaves in a supersonic gas jet, and ii) a second countercrossing laser beam producing a hot plasma whose expansion creates a channel. Both methods lead to significant density gradients. Injection of electrons in the wakefield is triggered by wave breaking in the density ramps. The injection is localized spatially and leads to the generation of relativistic electrons at the 100 MeV level with few-percent energy spread. The stability of this injection process is compared to the stability of the colliding pulse injection process and is found to be inferior for our experimental conditions. On the other hand, it is found that as the electron beam divergence is smaller in the case of gradient injection, the transverse emittance might be better.

8779-25, Session 6

Research with the 1 PW BELLA laser facility

Wim Leemans, Lawrence Berkeley National Lab. (United States)

No Abstract Available

8779-26, Session 6

Scattering instabilities and plasma dynamics in laser plasma wakefield accelerators

Karl M. Krushelnick, Univ. of Michigan (United States)

Recent experimental results using the HERCULES laser system at the University of Michigan will be discussed. We will describe measurements of the dynamics of ions and the electron beams from laser wakefield accelerator experiments at powers up to 200 TW.

These results include:

1) spatially resolved Raman scattering measurements as well as the first measurements of scattering from a "bubble" instability

2) measurements of electron beam filamentation

3) measurements of ion dynamics and laser channeling during the

interaction

4) effects of self-generated magnetic fields

Comparisons with simulations will also be discussed.

8779-27, Session 6

High energy, low energy spread electron bunches produced via colliding pulse injection

Cameron G.R. Geddes, Lawrence Berkeley National Lab. (United States)

No Abstract Available

8779-28, Session 7

Generation of electron beam and betatron x-ray sources from laser-driven atomic clusters *(Invited Paper)*

Liming Chen, Institute of Physics (China)

No Abstract Available

8779-29, Session 7

Effective generation of fast particles and short wavelength radiation from nano-structure targets irradiated by relativistic intensity laser pulse

Alexander Andreev, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

The main problem of laser target interaction physics is an efficiency of transformation of laser pulse energy into particle or radiation energy. Rather recently it was revealed that transformation of laser energy in ion energy increases at use a thin foils limited in size anywhere laser radiation absorption of such targets was not so high. In the present report it is offered to significantly increase target absorption and to optimize parameters of a relief and basic part of a target so that an absorbed energy is transferred to an accelerated particles and reflected (transmitted) energy is radiated as attosecond pulses. The choice of optimum characteristics of a target is made by means of analytical and multi-dimensional numerical modeling of a target set with characteristics near to optimum values. We investigated metall and plastic foils consisting of a substrate in the form of a few hundereds nanometers with different elements of a relief put on this substrate. The laser pulse irradiated targets had relativistic intensity and tens femtosecond duration. It was found that the optimal relief is capable to increase absorption of a target to extremely high values. The shape of profile does not change significantly the absorption but affect on a final object properties. An optimal target relief rises laser pulse absorption to maximal possible value and significantly improves X-ray photon yield. The effective scheme of generation of short dense electron bunches is offered at interaction on a big angle of incidence of a laser pulse with thin semi-limited foil. Streams of electron bunches can be used for generation of a short pulse EUV radiation at hitting of fast electrons a secondary target. It is shown, that at reflection from a target the laser wave of relativistic intensity is effectively converted in sequence of electromagnetic pulses of tens nanometer length, the following one after another through the period of an initial laser wave. Dependence of its parameters on angle of incidence and laser intensity is investigated. It is shown, that effective atto-pulse can be generated at the interaction of a laser pulse with a double foil target.

8779-30, Session 7

Coaction of strong electrical fields in laser irradiated thin foils and its relation to field dynamics

at the plasma-vacuum interface

Florian Abicht, Matthias Schnuerer, Julia Braenzel, Gerd Priebe, Alexander Andreev, Christian Koschitzki, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany); Sven Steinke, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany) and Lawrence Berkeley National Lab. (United States); Toma Toncian, Oswald Willi, Heinrich-Heine-Univ. Düsseldorf (Germany); Wolfgang Sandner, Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

The effective action of strong electrical fields on a beam of protons passing through a laser irradiated thin foil has been investigated. It is found to be different from the expected field dynamics arising from a combination of plasma-vacuum interfaces near the foil surface. The energy distribution function of protons propagating along the surface normal changes in a pronounced way, exhibiting a gap in the spectrum accompanied by up to two local maxima. The temporal behavior differs from expectations derived from the evolution of strong electrical fields at the plasma-vacuum interface, usually being considered responsible for fast ion acceleration during the initial stage of laser driven plasma expansion. This process of Target Normal Sheath Acceleration (TNSA) has been widely investigated and has been proposed for use in staged acceleration schemes. Our investigation reveals unexpected field effects in thin foils when irradiated with intense and ultra-short pulses with a very high temporal contrast. It suggests a revision of originally proposed ideas [1,2].

The experiments were performed with a laser accelerated proton beam, the probe, traversing a "plasma slab" created by ultra-short (80fs), high-intensity (~ 1 x 1019 W/cm2) laser irradiation of a 30 nm to 800 nm thick foil. Laser pulses with different temporal contrast and pulse duration have been used, both for the probe and for the plasma slab creation (the pump). The contrast exhibits a clear effect on the initial laser acceleration but not on the onset of the velocity redistribution of protons traversing the plasma slab. The probe beam experiences the above mentioned energy redistribution within a narrow energy interval which can be adjusted through the pump-probe delay. Surprisingly, this sharp redistribution occurs several tens of picoseconds after the laser (the pump) creates the plasma slab from the thin solid foil. The timing has been confirmed by turning the set-up from the longitudinal (protons transmit through the foil) to the transversal (protons travel along the foil surface) geometry. In the latter case the onset of the TNSA-fields became directly visible through the technique of proton streak deflectometry [3,4]. Analytical models and PIC-simulations are discussed to approach an understanding of the observation. Conclusions in respect to proposed staged laser driven ion acceleration are introduced.

1 – E. Fourkal et al., 2009 J. Plasma Phys. 75 235–50

2 – S.M. Pfotenhauer et al., 2010 New J. Phys. 12, 103009

3 – Th. Sokollik et al. 2008 Appl. Phys. Lett.92, 091503

4 – S. Ter-Avetisyan et al., 2008 Rev. Sci. Instrum. 79, 033303

8779-31, Session 7

Experimental test of TOF diagnostics for PW class lasers

Jan Prokupek, Institute of Physics of the ASCR, v.v.i. (Czech Republic) and Czech Technical Univ. in Prague (Czech Republic); Daniele Margarone, Daniel Kramer, Tomas Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Jirí Limpouch, Czech Technical Univ. in Prague (Czech Republic) and Institute of Physics of the ASCR, v.v.i. (Czech Republic); I Jong Kim, Tae Moon Jeong, Kee Hwan Nam, Gwangju Institute of Science and Technology (Korea, Republic of); Giuseppe

Bertuccio, Donatella Puglisi, Politecnico di Milano (Italy); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

New regime of PW class laser-matter interaction seeks for the new technology of in-situ diagnostics. Before constructing new kind of detectors one must test current diagnostics in new regime of laser-matter interaction. We present two types of time-of-flight (TOF) detectors, experimental tests and results are presented, demonstrating the possibility of their measuring capabilities in harsh conditions, namely the strong laser induced electromagnetic pulse (EMP). Small characterization of EMP was done from the detector responses. The well-known silicon-carbide (SiC) detector was successfully tested and particles where detected. The second measuring device was the detector based on secondary emission of electrons during transition of laser-generated particles. The experiment was carried Advanced Photonics Research Institute in Republic of Korea. The detectors show consistent results and sufficient capabilities for particle detection.

8779-32, Session 8

Bandwidth-stabilized water-window X-ray pulses from a laser-plasma driven undulator *(Invited Paper)*

Andreas Maier, Center for Free-Electron Laser Science (CFEL) (Germany)

Laser-plasma accelerators are prominent candidates for driving next-generation light sources, promising few-fs x-ray pulses perfectly synchronized to an optical laser, thus enabling pump-probe experiments with unprecedented temporal resolution. We report on a recent experiment demonstrating spontaneous undulator radiation from a laser-plasma accelerator, with photon pulses freely tunable over a range from 100 to 300 eV. Using a set of specifically designed multilayer mirrors, we can selectively choose the central photon pulse energy and bandwidth and focus the x-ray pulses on target. Assuming chirped electron bunches, as expected from laser-plasma accelerators, the pulses can be compressed to the 1 fs level and below.

8779-33, Session 8

A bright neutron source driven by a short pulse laser

Markus Roth, Technische Univ. Darmstadt (Germany)

Neutrons are a unique tool to alter and diagnose material properties, and to exciting nuclear reactions, for many applications. Accelerator based spallation sources provide high neutron fluxes for research, but there is a growing need for more compact sources with higher peak brightness, whether fast or moderated neutrons. Intense lasers promise such as source, readily linkable to other experimental facilities, or deployable outside a laboratory setting. We present experimental results on the first short-pulse laser-driven neutron source powerful enough for radiography. A novel laser-driven ion acceleration mechanism (Breakout Afterburner), operating in the relativistic transparency regime, is used. Based on the mechanism's advantages, a laser-driven deuteron beam is used to achieve a new record in laser-neutron production, in numbers, energy and directionality. This neutron beam is a highly directional pulse < 1 ns at ? 1 cm from the target, with a flux > 40/?2, and thus suitable for imaging applications with high temporal resolution. The beam contained, for the first time, neutrons with energies of up to 150 MeV. Thus using short pulse lasers, it is now possible to use the resulting hard x-rays and neutrons of different energies to radiograph an unknown object and to determine its material composition. Our data matches the simulated data for our test samples.

1Supported by NNSA and the LANL Rosen Scholar Program.

8779-34, Session 8

A table-top laser-based source of short, collimated, ultra-relativistic positron beams

Gianluca Sarri, Queen's Univ. Belfast (United Kingdom)

An ultra-relativistic electron beam passing through a thick, high-Z solid target triggers an electromagnetic cascade, where a large number of high energy photons and electron-positron pairs are produced mainly via the bremsstrahlung and the Bethe-Heitler processes, respectively. These mechanisms are routinely exploited in conventional accelerators, such as the Electron-Positron Collider (LEP), to generate ultra-relativistic positron beams. By exploiting the same physical process, we present here the first experimental evidence of the generation of ultra-short (35 fs), highly collimated (3 mrad) and ultra-relativistic (150 MeV) positron beams following the interaction of a laser-wakefield accelerated electron beam with high-Z solid targets. The modest laser parameters (25 TW) make this the first demonstration of a table top source of relativistic positron beams. Besides their importance for fundamental science, we anticipate that these beams will be of direct relevance to the laboratory study of astrophysical leptonic jets and their interaction with the interstellar medium.

8779-35, Session 8

Laser-driven dielectric electron accelerator for radiobiology researches

Kazuyoshi Koyama, The Univ. of Tokyo (Japan) and High Energy Accelerator Research Organization (Japan); Yosuke Matsumura, Mitsuru Uesaka, Aimidula Aimierding, The Univ. of Tokyo (Japan); Mitsuhiro Yoshida, Takuya Natsui, High Energy Accelerator Research Organization (Japan)

In order to estimate a health risk associated with a low radiation dose, the fundamental process of the radiation effects on a living cell must be understood. It is desired that an electron bunch or photon pulse precisely knock a cell nucleus and DNA. Moreover, it is required that the whole chemical and biological process is observed in situ by using an optical microscope and probe beams. In order to obtain the irradiation area smaller than 1μm in diameter, the required electron energy is in the nonrelativistic energy range from 100 keV to 1 MeV. The electronic charge of 0.01 fC to 0.1 fC is sufficient if the beam is concentrated in the 1μm diameter spot.

A laser driven dielectric accelerator, e.g. photonic crystal accelerator (PCA) is capable of delivering fs-pulse of nanobeam. We chose a phase-modulation-mask-type laser-driven dielectric accelerator (PLDA) as a pinpoint irradiation device from the viewpoint of the fabrication technology. The PLDA consists of a couple of transmission gratings placed across the acceleration channel from each other. Gratings are made of a transparent material such as the silica, diamond, etc. The longer optical path length through the grating bar retard the phase of the laser light. Therefore, a spatially alternating electric field is introduced by properly tuning the thickness of the bar. The grating period LG must be equal to v/f to accelerate the electron by the alternating field, where v is the particle speed and f is the laser frequency. The accelerator is energized by the face-to-face irradiation of laser pulses in an orthogonal direction to the acceleration channel. The direction of the polarization of the laser pulse is parallel to the channel. The acceleration field strength is limited by the threshold intensity of the optical damage of the dielectric material.

The simulation results by using the FDTD code, Meep showed that the minimum grating period is a half wavelength of the laser light. This value restricts the initial electron speed of v_ini=0.5c (79 keV), where c is the speed of light in a vacuum. A width of the acceleration channel is chosen to be a quarter wavelength of the laser chosen by considering the diffraction blurring from the pillar edge. The 1-MeV electron bunch will be obtained in a 0.5-mm long acceleration channel at the laser intensity of 10^13 W/cm^2. We are performing the numerical simulation of the laser propagation to determine the optimum structure of the grating and focusing optics.

The best system to reduce the required laser energy is to restrict an illumination area and the laser pulse to the position of the electron bunch. The total required laser energy is 4 mJ to obtain 1 MeV electron bunch. A couple of five-sequential pulse (0.4 mJ, 400fs each pulse) is focused on the PLDA. Since the modern fiber laser is suitable for delivering 4-5 mJ, 400fs pulses, we are developing Yb-fiber laser oscillator, amplifier and the phase and polarization control devices.

8779-36, Session 8

Numerical modeling of dielectric laser accelerator structures

Benjamin Cowan, Robert K. Crockett, Dan T. Abell, Brian T. Schwartz, Stephen D. Webb, Tech-X Corp. (United States)

Dielectric laser-driven accelerators (DLAs) hold promise for high-gradient acceleration because the high breakdown threshold of dielectric materials at optical frequencies allows higher electric fields than in conventional metal structures. Concepts for DLA structures include photonic crystal waveguides, which can confine a phase-matched optical mode in an all-dielectric structure, and grating pairs, which use a phase mask to match the phase of a transversely-incident laser pulse with a propagating beam. Here we present simulation studies of several key aspects of dielectric laser acceleration. One of these examines beam-driven wakefields in photonic crystal fiber structures. We use self-consistent particle-in-cell simulations to determine the beam-driven fields, and parametrize the impact of wakefields on a propagating bunch. We then use that parametrization to study the stability of particle bunches in a DLA over collider length scales. We also present modeling of material dispersion and nonlinearities, and the effects of these optical parameters on acceleration. Finally, we show detailed computations of accelerating modes in photonic crystal fibers.

8779-37, Session PS

Thomson Parabola spectrometry as diagnostics of fast ion emission from laser-generated plasmas

Lorenzo L. Torrisi, Mariapompea Cutroneo, Univ. degli Studi di Messina (Italy); Salvatore Cavallaro, Univ. degli Studi di Catania (Italy); Lucio Andò, Univ. degli Studi di Messina (Italy); Jiri Ullschmied, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic)

High intensity lasers generate hot plasmas irradiating solid matter in vacuum. Plasma properties depend strongly on the laser and target parameters and on its developing conditions. The physical characterization of such non-equilibrium plasma can be performed using different fast diagnostic techniques based on the detection of energetic charge particles and photons.

Thomson parabola spectrometry, from single laser shots, permits to give a lot of information about the plasma ion emission, the charge-to-mass, ion energy and charge state distributions, furnishing data useful for the understanding of the physical mechanisms involved in the plasma kinetics.

Measurements performed at intensities of the order of 1016 W/cm2, using the Asterix laser of PALS laboratory of Prague, have been obtained irradiating thin targets in target normal sheath acceleration (TNSA) conditions, as will be presented and discussed.

8779-38, Session PS

Relativistic electron generation in laser produced ion channels

Neda Naseri, Tech-X Corp. (United States) and Univ. of Alberta (Canada); Denis Pesme, Ecole Polytechnique (France) and Univ. of Alberta (Canada); Wojciech Rozmus, Univ. of Alberta (Canada)

The interaction of high energy relativistic laser pulses with underdense plasmas has been extensively studied in experiments and by simulations [1]. We present results of 3D PIC simulations and the corresponding theoretical analysis of relativistic self-focusing, laser pulse channeling, surface wave generation and electron acceleration [2]. Specifically, we study the interaction of laser pulses having their intensity I ?2 in the range [1019, 1020] W/cm2 ?m2, focused in a plasma of electron density n0 such that the ratio n0/nc lies in the interval [10-3, 10-1], nc denoting the critical density.

For laser pulse powers PL above the threshold for channeling Pch = 1.09 Pc, Pc denoting the critical power for self-focusing, we have observed the stability of the laser pulse propagation as a single mode in an electron free channel as predicted in Ref. [3], in the limit of sufficiently underdense plasmas, namely for n ≤ 0.1 nc. These results apply to picosecond laser pulses, and a very good agreement has been observed between the stationary analytical theory predictions [3] and our PIC simulations.

The laser front is observed to give rise to a surface wave [4] which propagates along the sharp boundaries of the electron free channel created by the laser pulse. The mechanism responsible for the generation of the fast electrons observed in the PIC simulations is then analyzed by means of a test particles code. It is thus found [2] that the fast electrons are generated by the combination of the acceleration by the surface wave and of the betatron process [5]. The latter is a direct laser acceleration process corresponding to the resonance between the transverse electron oscillations caused by the radial charge separation electric field and the motion due to the periodic laser wave fields. The maximum electron energy observed in the simulations is scaled as a function of PL/Pc ; it reaches 350 -400 MeV for PL/Pc = 70 - 140.

[1] L. Willingale, P. M. Nilson, A.G.R. Thomas, et al. Phys. Rev. Lett. 106, 105002 (2011); S. Kneip, S. R. Nagel, C. Bellei, et al. Phys. Rev. Lett. 100, 105006 (2008); S.P.D. Mangles, B. R. Walton, M. Tzoufras, et al. Phys. Rev. Lett. 94, 245001 (2005).

[2] N. Naseri, D. Pesme, W. Rozmus, and K. Popov, Phys. Rev. Lett. 108, 105001 (2012).

[3] A. Kim, M. Tushentsov, F. Cattani, et al. Phys. Rev. E 65, 036416 (2002).

[4] T.C. Chiou, T. Katsouleas, C. Decker, et al. Phys. Plasmas 2, 310 (1995).

[5] A. Pukhov, Z-M Sheng, J. Meyer-ter-Vehn, Phys. Plasmas 6, 2847 (1999).

8779-39, Session PS

Laser-ion acceleration from transparent overdense plasmas at the Texas Petawatt

Ishay Pomerantz, Joel Blakeney, Lindsay Fuller, Erhard W. Gaul, Gillis Dyer, A. R. Meadows, Chunhua Wang, Todd Ditmire, The Univ. of Texas at Austin (United States); Björn Manuel Hegelich, Donald C. Gautier, Rahul Shah, Daniel Jung, Juan C. Fernandez, Los Alamos National Lab. (United States)

A steady increase of on-target laser intensity with also increasing pulse contrast is leading to light-matter interactions of extreme laser fields with matter in new physics regimes. At the Texas Petawatt laser (TPW) we have realized interactions in the transparent-overdense regime, which is reached by interacting a highly relativistic, ultra-high contrast laser pulse with a solid density ultrathin target. The extreme fields in the laser focus are turning the overdense, opaque target transparent to the laser by the relativistic mass increase of the electrons. Thus, the interaction becomes volumetric, increasing the energy coupling from laser to plasma.

Using plasma mirrors to increase the on-target contrast ratio, we demonstrated generation of over 60 MeV proton beams with pulse energies not exceeding 40 J (on target). We further applied these beams to generate neutrons using a Be converter, and demonstrated yields of over 109 neutrons per shot.

I will discuss these results and the plans for an extensive campaign to improve the TPW contrast ratio planned for 2013. Following this campaign we expect ion beam energies to scale over 150 MeV/amu. The shown results now approach the limits set by many applications from ICF diagnostics over ion fast ignition to medical physics.

8779-40, Session PS

Characterization of laser accelerated electron bunches for potential radiotherapy applications

Lorenzo Fulgentini, Federica Baffigi, Antonio Giulietti, Istituto Nazionale di Ottica (Italy); Luca Labate, Istituto Nazionale di Ottica (Italy) and Instituto Nazionale di Fisica Nucleare (Italy); Yuji Oishi, Central Research Institute of Electric Power Industry (Japan) and Instituto Nazionale di Fisica Nucleare (Italy) and Istituto Nazionale di Ottica (Italy); Leonida A. Gizzi, Istituto Nazionale di Ottica (Italy) and Instituto Nazionale di Fisica Nucleare (Italy)

In the last few years, a novel class of table-top electron linear accelerators driven by ultra-short intense laser pulses has been developed in many laboratories, which allows relativistic electron beams to be obtained over accelerating distances much shorter (in principle, up to 1000 times shorter) than in conventional RF-linacs. In fact, Laser Wake Field Accelerators (LWFA) take advantage of the high fields developed and supported in plasma: in the LWFA the electrons trapped in the plasma wave are accelerated almost at the speed of light. This enables generation of electron bunches whose kinetic energy and dose delivered per unit time may be suitable for radiotherapy applications such as IORT. In particular, performances have been attained very close to the output of conventional Radio Frequency (RF) driven accelerators used for Intra-Operative Radiation Therapy (IORT). Due to its small size (laser-based accelerators are usually considered "table-top") and to the acceleration process occurring over a tiny distance, a laser-based accelerator employed for the cancer radiotherapy can basically override most of the problems related to the RF linacs.

We characterized electron bunches created using 40 fs laser pulses generated by a 3 TW table-top laser system focused on laminar gaseous target produced by a supersonic gas-jet of He or N2. The laser-gas interaction was monitored using interferometric and shadowgraphic techniques. The electron bunches were analyzed using a Lanex screen and a magnetic spectrometer to investigate spectral properties. With this set-up, we have been able to generate electrons with energies up to some MeV with good reproducibility and spatial uniformity. This regime will be further investigated (with complete dosimetric characterization, assessment of radiobiological effects) in view of its exploitation for potential radiotherapy applications.

8779-41, Session PS

Advanced simulation methods for laser-plasma injectors and acceleration stages

Benjamin Cowan, Estelle Cormier-Michel, Eric Hallman, Neda Naseri, Tech-X Corp. (United States)

We present several computational methods to improve the accuracy and performance of laser-plasma acceleration (LPA) simulations, from self-injection through multi-GeV acceleration stages. One of these, for injection simulations, involves loading the plasma region in which beam particles originate with higher particle statistics than in other locations. By doing this, we can significantly increase the number of macroparticles in the injected beam. We show that this technique captures much finer detail of particle phase space than does uniform loading, and results in lower noise. We demonstrate convergence of key beam parameters using this method. A method for improving the accuracy and performance of meter-scale acceleration stages involves solving for the beam self-fields in the bunch rest frame. We demonstrate that this method results in much lower numerical emittance growth than more conventional methods. We also present a controlled dispersion algorithm that results in more accurate laser pulse group velocity, and hence more accurate beam phase space, than the standard electromagnetic update. Finally, we show orders of magnitude performance enhancement over standard PIC simulations by using several of these techniques in a Lorentz boosted frame.

8779-42, Session PS

Prepulse induced microstructured plasma with melted and solid targets: formation, properties & prospects to relativistic laser-plasma interaction

Darya Uryupina, Alexey Lar'kin, Konstantin Ivanov, Sergey Shulyapov, Roman Volkov, Andrei Savel'ev, Lomonosov Moscow State Univ. (Russian Federation); Sergey Pikuz, Joint Institute for High Temperatures (Russian Federation); Andrei Brantov, Valery Bychenkov, P.N. Lebedev Physical Institute (Russian Federation); Claude Fourment, Fabien Dorchies, Benoit Chimier, Vladimir T. Tikhonchuk, Univ. Bordeaux 1 (France); Franck Gobet, Medhi Tarisien, David Denis-Petit, Fazia Hannachi, Thomas Bonnet, Maud Versteegen, Institut National de Physique Nucléaire et de Physique des Particules (France)

The use of microstructured, space-limited targets for laser-plasma experiments is a promising way for the increase of plasma source parameters due to enhanced absorption and effects of local field amplification. However, very high contrast of the laser pulse, especially at relativistic intensities, is needed to avoid structures destruction and formation of large preplasma.

We present our recent results on diagnostics of the plasma created by a high intensity femtosecond laser pulse on the modified by a weak prepulse surface of melted metal target. We have shown that the introduction of prepulse with energy of few tens of microjouls outrunning the main pulse over 10 nanoseconds leads to the formation of quasi-stable from shot to shot dense microstructures having the shape of jets tens of microns long, emitted along the laser propagation direction. The fully relativistic 3D PIC simulation revealed that the local electric field amplification at the jets edges occurring at interaction of the main pulse with the structures leads to the stochastic character of the electrons movement and finally to the appreciably increased particles mean energy (up to MeV). Our simulation shows that this approach is applicable for generation of harder x-rays, fast electrons and ions in a wide range of laser intensities (from moderate to relativistic).

In our experiments we used a laser pulse delivered by Ti:Sa laser system (pulse duration – 40 fs, energy on target – up to 50 mJ, wavelength – 800 nm, repetition rate – 10 Hz, peak intensity – 5x10^18 W/cm^2). The prepulse with varied time delay (0-15 ns) and energy (0-1 mJ) was created by reflected from a beam-splitter part of the uncompressed main pulse. Melted gallium at 300 C was used as a target. The use of liquid metal also avoids the necessity of permanent target movement and permits to create a stable source of short x-ray pulses operating at high repetition rate.

At moderate intensity (10^17 W/cm^2) we achieved a fourfold increase of mean hot electron energy (from 20 to 80 keV) and appreciable growth of hard x-ray yield from plasma, formed on a microstructured by the prepulse surface of melted Ga target.

The x-ray and electron spectra of the plasma, driven by a sub-relativistic to relativistic (1-5x10^18 W/cm^2) femtosecond laser pulse, are measured at varied prepulse parameters showing the influence of the target surface modification on the parameters of the plasma source. The dynamics of the structured preplasma is also studied. The results are discussed with 3D PIC and 1D hydrodynamic simulations of laser-plasma interaction.

At the same time the optical shadowgraphy of the prepulse created plasma supported by numerical simulations of plasma dynamics revealed that the structuring of the surface is possible also for initially solid targets, showing a possibly wide applicability of our approach for plasma source enhancement.

8779-43, Session PS

Electron beams generation by laser wakefield acceleration in tapered capillaries

Cristian Ciocarlan, Univ. of Strathclyde (United Kingdom) and Horia Hulubei National Institute of Physics and Nuclear Engineering (Romania); Mark Wiggins, Salima Abu-Azoum, Univ. of Strathclyde (United Kingdom)

The gas-filled capillary discharge waveguide (CDW) is a commonly applied accelerating structure for the laser wakefield accelerator (LWFA) because an intense femtosecond laser pulse can be successfully guided over several centimeters, leading to the generation of GeV - scale electron beams. Simulations have shown that tapering the longitudinal plasma density, hence increasing the dephasing length between wakefield and beam leads to significant enhancement of the final electron energy in a single accelerating stage.

It is presented realisation of linearly tapered CDWs, manufactured using a femtosecond laser micromachining technique pioneered at the University of Strathclyde]. The alumina waveguide has a length of 40 mm and a diameter that decreases linearly from 320 ?m to 270 ?m along its length, and is filled with plasma generated by application of a 20 kV pulse to hydrogen gas injected into the capillary.

The transverse plasma density profile at either end is obtained with a detection system measuring the Stark-broadened hydrogen spectral line emission. The whole length of CDW and also the plasma “plum” at the exits - several centimeters out of capillary, have been investigated. At a gas backing pressure of 60 mbar, the on-axis, time-integrated density increases from 0.8 x 10^18 el/cm3 (wider end) to 1.5 x 10^18 el/cm3 (narrower end) thus indicating a tapered longitudinal plasma density.

Waveguiding of a low power, 50 fs duration laser pulse is demonstrated and, despite a slight mismatch of the laser focal spot size with respect to the capillary entrance size, efficient guiding of the Gaussian-shaped laser pulse is obtained. Energy transmission of 80% is obtained for optimal delay of the laser pulse arrival time with respect to the discharge current pulse. Comparison is made, for identical laser conditions (intensity of 1.6 x 10^18 W/cm2), between three tapering configurations: density decreasing with distance (negative taper), density constant (no taper) and density increasing with distance (positive taper), over the same capillary length of 40 mm in the (average) plasma density range of 3-6 x 10^18 el/cm3.

8779-44, Session PS

Numerical study of shock wave acceleration

Elisabetta Boella, Insituto Superior Técnico (Portugal)

During the past year, growing interest has developed around the topic of laser-driven electrostatic shock waves in near critical density plasmas. Experiments and numerical simulations have, in fact, demonstrated how the Shock Wave Acceleration (SWA) mechanism can be used to generate ion beams having energy and energy spread suitable for tumor treatment. However, the optimal conditions leading to the production of a high-quality ion beam are still under investigation. In this work, we will present a detailed numerical study of the SWA process carried out with a reduced one dimensional electrostatic code that, despite of its simplicity allows us to capture all the relevant physics involved and, at the same time, provides the advantage of a reduced computational time. We will show the role that different plasma parameters, such as plasma profile density and plasma temperature, play during the shock formation and ion reflection stages. Moreover, we will discuss the advantages of using an initially exponentially decaying plasma profile and, with the final aim of optimizing the ion acceleration process, we will analyze the influence of the target size and of the decaying length on the quality of the beam.

8779-45, Session PS

Micro-radiography with a new laser-electron gun

GianCarlo Bussolino, Istituto Nazionale di Ottica (Italy); Anatoly Y. Faenov, Joint Institute for High Temperatures (Russian Federation) and Japan Atomic Energy Agency (Japan); Antonio Giulietti, Istituto Nazionale di Ottica (Italy); Danilo Giulietti, Istituto Nazionale di Ottica (Italy) and Instituto Nazionale di Fisica Nucleare (Italy); Petra Koester, Istituto Nazionale di Ottica (Italy); Luca Labate, Istituto Nazionale di Ottica (Italy) and Instituto Nazionale di Fisica Nucleare (Italy); Tadzio Levato, Istituto Nazionale di Ottica (Italy) and Univ. di Roma (Italy) and Institute of Physics of the ASCR, v.v.i. (Czech Republic); Tania Pikuz, Joint Institute for High Temperatures (Russian Federation) and Japan Atomic Energy Agency (Japan); Leonida A. Gizzi, Istituto Nazionale di Ottica (Italy) and Instituto Nazionale di Fisica Nucleare (Italy)

A new type of laser-electron gun, based upon the use of the last generation of Titaniun-sapphire, ultra-short pulse lasers has been used to drive electrons acceleration in a underdense plasma generated by gas-cluster targets.

The experiments have been implemented at the Intense Laser Irradiation Laboratory (ILIL) at National Institute of Optics (CNR-INO) in Pisa(1) using a high-contrast 40 fs duration 2.5 TW laser pulse with an argon cluster target. This setup allows the electrons acceleration to MeV energy in a few millimeters in a very compact design and efficient electron beam generation. This kind of source has several application and one could be the electron contact micro-radiography for relatively large (square centimetres) areas.

Two cm-scale samples were used: the first one included an electronic circuit, two leaves, three Al foils (13 mm in thickness) and a glass fiber, while second one included a scorpion, two leaves, an electronic circuit, a tantalum thin foil (5 mm in thickness) These samples were placed at about 10 cm from the laser interaction point and, just after the sample, in direct contact, two radiochromic dosimetry films (GAFCHROMIC® MD-55) were insert. An high definition flatbed color image scanner was used, in transmission mode, for measuring these exposed films.

Scans of films gave measure of the sensitivity and of the high resolution capabilities of the system. In particular, looking at the scan of one leaf, included in the first sample, some local structures can be clearly seen: these details correspond to a region where a chlorophyll rich area is still visible in an otherwise dried, yellow tissue. Comparison of our electron radiography with the original leaf shows that the green region has a higher absorption than the surrounding yellow region (probably due to the presence of water in the green region). This is a clear indication of the sensitivity of electron imaging to the chemical or structural differences in our sample, with possibility of non-destructive analysis of samples especially of biological.

This is relevant to medical and biological imaging using radiation and particle beams and shows that our new laser-electron gun can be successfully applied to transmission electron radiography of thin and thick cm scale samples in a simple contact transmission configuration. The experimental results are very encouraging and the possibility of the micro-radiography has been demonstrated for cm scale samples up to several mm depth.

(1)L. A. Gizzi, C. A. Cecchetti, A. Giulietti, D. Giulietti, P. Koester, L. Labate, T. Levato, N. Pathak, “Thomson Scattering Imaging From Ultrashort Ultraintense Laser Interaction With Gas,” IEEE Transaction on plasma science, 39, N° 11, (2011).

8779-46, Session PS

High energy electrons from interaction with a 10 mm gas-jet at FLAME

Gabrielle Grittani, Istituto Nazionale di Ottica (Italy) and INFN (Italy) and Univ. of Pisa (Italy); Maria Pia Anania, Univ. of Strathclyde (United Kingdom); Giancarlo Gatti, Istituto Nazionale di Fisica Nucleare (Italy); Danilo Giulietti, Univ. di Pisa (Italy); Masaki Kando, Japan Atomic Energy Agency (Japan); Miroslav Krus, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Luca Labate, Istituto per i Processi Chimico-Fisici (Italy); T. Levato, Consiglio Nazionale delle Ricerche (Italy); Yu Oishi, RIKEN (Japan); Francesco Rossi, Istituto Nazionale di Fisica Nucleare (Italy); Leonida A. Gizzi, Consiglio Nazionale delle Ricerche (Italy)

In this poster we discuss the spectra of the electrons produced in the laser-plasma acceleration experiment at FLAME. Here a <30 fs laser pulse is focused via an f/10 parabola in a focal spot of 10 _m diameter into a 1.2 mm by 10 mm rectangular Helium gas-jets at a backing pressure ranging from 5 to 15 bar. The intensity achieved exceeds 1019 Wcm2, which is enough to drive Laser Wakefield Acceleration of electrons. In our experiment the laser is set to propagate in the gas-jet along the longitudinal axis to use the 10 mm gas-jet length and to evaluate the role of density gradients. The propagation of the laser pulse in the gas is monitored by means of a Thomson scattering optical imaging. Accelerated electrons are set to propagate for 47,5 cm before being detected by a scintillating screen to evaluate bunch divergence and pointing. Alternatively, electrons are set to propagate in the field of a magnetic dipole before reaching the scintillating screen in order to evaluate their energy spectrum. The spectral properties of the accelerated electrons are then studied to infer the regime of acceleration occurring in the plasma. Our experimental data show highly collimated bunches (<1 mrad) with a relatively stable pointing direction (<10 mrad). Typical bunch electron energy ranges between 50 and 200 MeV with occasional events of higher energy up to 1GeV. The retrieved spectra are typically characterized by a large energy spread. In the poster we will show the main results of optical and electron measurements and will compare the range of measured experimental parameters with the expected PIC numerical simulation. This will enable us to identify the acceleration regime in our specific laser-plasma acceleration experiment.

8779-50, Session 10

The production of patient dose level 99mTc medical radioisotope using laser-driven proton beams

Robert J. Clarke, Sam Dorkings, Rutherford Appleton Lab. (United Kingdom)

The medical isotope 99mTc is used in over 30 million nuclear medical procedures, accounting for over 80% of the worldwide medical isotope usage. Its supply is critical to the industry and a worldwide shortage is expected within the next few decades as current fission reactors used for its generation reach their end of life. The cost of build and operation of replacement reactors is high and as such alternative production mechanisms are of high interest. Laser-accelerated proton beams have been widely discussed as being able to produce PET isotopes once laser architecture evolved to high repetition rates and energies. Recent experimental results performed on the Vulcan Laser Facility in the production of 99mTc through 100Mo (p,2n) 99mTc demonstrate the ability to produce this critical isotope at the scales required for patient doses using diode pumped laser architecture currently under construction. The production technique, laser and target requirements are discussed alongside a timeline and cost for a prototype production facility

8779-51, Session 10

High energy ion acceleration and neutron production using relativistic transparency in solids

Markus Roth, Technische Univ. Darmstadt (Germany)

In a recent campaign at LANL we have achieved proton energies exceeding 150 MeV and deuteron energies exceeding 180 MeV. We also have accelerated heavier ions to the point where the use in medical applications become promising. Furthermore we have been successful in converting those ion beams into a beam of neutrons that might be valuable to application in medicine, material science and security applications. With more than 10^11 neutrons in a single shot and energies up to 200 MeV these neutrons have been used for the first time to image a secondary object, using just 60 J of laser energy.

With the upcoming high contrast version of PHELIX, operational since a few weeks, we intend to continue this endeavor using shorter pulse length and up to four times the energy of TRIDENT. Simulations indicate proton energies of about 230 MeV, using cryogenic targets.

8779-52, Session 10

Radiobiology at ultra-high dose employing laser-driven ions

Marco Borghesi, Queen's Univ. Belfast (United Kingdom) and Institute of Physics of the ASCR, v.v.i. (Czech Republic); Fiona Hanton, Giuseppe Schettino, Domenico Doria, Satyabrata Kar, Matthew Zpef, Queen's Univ. Belfast (United Kingdom); Kevin Prise, Queen's University (United Kingdom)

The ultrashort duration of laser-driven multi-MeV ion bursts offers the possibility of radiobiological studies at extremely high dose rates. Employing the TARANIS Terawatt laser at Queen's University, the effect of proton irradiation at MeV-range energies on live cells has been investigated at dose rates exceeding 109 Gy/s as a single exposure. A clonogenic assay showed consistent lethal effects on V-79 live cells, which, even at these dose rates, appear to be in line with previously published results employing conventional sources.

8779-53, Session 11

First order concept beamline design for particle therapy with laser accelerated protons

Umar Masood, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Michael Bussmann, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Wolfgang Enghardt, OncoRay - National Ctr. for Radiation Research in Oncology (Germany) and Helmholtz-Zentrum Dresden-Rossendorf e.V. (Germany); Leonhard Karsch, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Florian Kroll, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Jörg Pawelke, OncoRay - National Ctr. for Radiation Research in Oncology (Germany) and Helmholtz-Zentrum Dresden-Rossendorf e.V. (Germany)

The recent advancements in the field of laser driven particle acceleration have made Laser-based Ion Beam Therapy (LIBT) an attractive alternative to existing synchrotron and cyclotron based Ion Beam Therapy (IBT) facilities. A highly focused ultra intense laser pulse (I ?^2 > 10^19 Wcm^-2 ?m^-2) interacts with thin metal targets (up to few ?m thickness) and generates pulsed proton beams with exponentially decaying energy spectrum and large energy dependent divergence angles (~15-40 deg.), in a well established acceleration process known as Target Normal Sheath Acceleration (TNSA). Maximum proton energies of ~67.5 MeV have been experimentally recorded, which are not yet sufficient for radiation therapy purposes, but scaling models show higher energies are reachable with increased laser power and new target geometries. The development of next generation Peta-watt laser systems such as Petawatt ENergy Efficient Laser for Optical Plasma Experiments (PENELOPE), Dresden, Germany promises to reach therapeutic energies in near future.

Due to the inherent laser-based acceleration process we can assume the laser accelerated proton (LAP) beams with therapeutic energies we might get from future experiments would be far from mono-energetic beams (?E/E ~ 0.1-1%), currently achievable by conventional accelerators at existing IBT facilities. Low repetition rates require high dose per shot to be delivered to keep treatment time within few minutes which need efficient capturing and energy selection system. This demands a new approach for tumor irradiation schemes and transport beamline design. In this study we present a new dose deposition model and simulation results for our concept of a doubly achromatic overhead 360 degree rotating compact gantry design (radius ~2.50 m) for LIBT.

For this study we have scaled existing experimental energy spectra to therapeutic energies, employing a conservative approach. A new concept for uniform dose deposition has been developed to utilize maximum available LAP fluence per shot by superimposing individual depth dose profiles with broad energies in an assorted scheme to achieve flat-top Spread Out Bragg Peak (SOBP). We call this model as Broad-Energy Assorted depth-Dose-deposition (BEAD). Using BEAD regime, with enough particles on the patient surface provided by the laser and beamline, only 15 LAP shots are required to achieve normalized SOBP (±3%) of 5cm width at 15cm depth, with maximum ?E/E = 24.5% and minimum ?E/E = 3.3%. This provided the pre-requisites for the gantry design.

Owing to the pulsed nature of LAP, pulsed magnets have been considered for the gantry design. They provide a very compact solution for transporting high rigidity particles and have been successfully used to capture and collimate LAP. Advantageous pulsed solenoid capturing

has been utilized to couple laser-target with transport beamline. The designed gantry includes Integrated Shot-to-shot broad-Energy Selection System (ISESS) using pulsed powered dispersive magnets, capable of filtering and transporting energy bandwidths of ?E/E = 3-26% from laser-target to patient table. Protection from the unwanted radiation has also been considered in the design. Experimental tests of pulsed beam-transport elements have been started.

In the talk the concept is presented and the basic features are explained.

8779-54, Session 11

Towards laser driven proton therapy of cancer: status of the Dresden program

Karl Zeil, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Michael Baumann, OncoRay - National Ctr. for Radiation Research in Oncology (Germany) and Helmholtz-Zentrum Dresden-Rossendorf e.V. (Germany) and Universitätsklinikum Carl Gustav Carus Dresden (Germany); Elke Beyreuther, Thomas E. Cowan, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Wolfgang Enghardt, OncoRay - National Ctr. for Radiation Research in Oncology (Germany) and Helmholtz-Zentrum Dresden-Rossendorf e.V. (Germany) and Universitätsklinikum Carl Gustav Carus Dresden (Germany); Leonhard Karsch, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Stephan D. Kraft, Florian Kroll, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Lydia Laschinsky, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Josefine Metzkes, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Melanie Oppelt, Christian Richter, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Roland Sauerbrey, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Michael Schürer, OncoRay - National Ctr. for Radiation Research in Oncology (Germany); Ulrich Schramm, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Jörg Pawelke, OncoRay - National Ctr. for Radiation Research in Oncology (Germany) and Helmholtz-Zentrum Dresden-Rossendorf e.V. (Germany)

Proton beams by their well-confined energy-loss in matter are a promising tool for the improvement of radiotherapy of cancer and are currently under intense medical investigation. Wider clinical use, however, is limited by the complexity and expense of current proton and ion accelerators. Compact laser driven proton therapy accelerators are discussed as a promising alternative, yet require substantial development in reliable beam generation and transport, but also in dosimetric protocols as well as validation in radiobiological studies.

In our talk, we will present the first direct and dose controlled comparison of the radiobiological effectiveness (RBE) of intense proton pulses from a laser driven accelerator with conventionally generated continuous proton beams, showing no dependence of the RBE on the different beam properties [1]. Controlled dose delivery, precisely online and offline monitored for each of the ~ 4000 proton pulses, resulted in an unprecedented relative dose uncertainty of below 10%, using approaches scalable to radiotherapy applications.

In parallel to the development of laser driven proton therapy accelerators, an advancement in instrumentation for laser driven protons is essential. Most importantly, these new diagnostic tools need to speedwise match the repetition rates of state-of-the-art high power laser systems and need to be adapted to the harsh plasma environment of laser based accelerators, not neglecting their fitment to the properties of laser accelerated proton pulses such as the high flux and the broad energy spectrum.

We will present three types of scintillator-based detectors, all being optimized for specific stages of the experimental chain: a one-dimensional space- and energy-resolved detector for online spectral stability control of the acceleration performance [2], a two-dimensional space- and energy-resolved detector for source characterization measurements, and a three-dimensional detector for precise dose verification in a water-equivalent medium with regards to medical quality assurance [3].

[1] K. Zeil, et al.: Dose-controlled irradiation of cancer cells with laser-accelerated proton pulses, Appl. Phys. B (2012)

[2] J. Metzkes, et al.: A scintillator-based online detector for the angularly resolved measurement of laser-accelerated proton spectra, Review of Scientific Instruments, in print

[3] F. Kroll, et al.: Investigations on the determination of three-dimensional dose distributions using scintillator blocks and optical tomography, submitted

8779-56, Session 11

Laser-driven nanosecond proton source and its applications

Jianhui Bin, Klaus Allinger, Ludwig-Maximilians-Univ. München (Germany) and Max-Planck-Institut für Quantenoptik (Germany); Walter Assmann, Guido A. Drexler, Anna A. Friedl, Dietrich Habs, Peter Hilz, Ludwig-Maximilians-Univ. München (Germany); Nicole Humble, Technische Univ. München (Germany); Daniel Kiefer, Max-Planck-Institut für Quantenoptik (Germany); Wenjun Ma, Ludwig-Maximilians-Univ. München (Germany); Doerte Michalski, Michael Molls, Technische Univ. München (Germany); Sabine Reinhardt, Ludwig-Maximilians-Univ. München (Germany); Thomas E. Schmid, Olga Zlobinskaya, Technische Univ. München (Germany); Joerg Schreiber, Ludwig-Maximilians-Univ. München (Germany) and Max-Planck-Institut für Quantenoptik (Germany); Jan J. Wilkens, Technische Univ. München (Germany)

The introduction of nanometer thin targets and ultrahigh contrast laser pulses has enabled a quantum leap in laser particle acceleration, offering much improved ion pulses in comparison to plasma expansion schemes such as target normal sheath acceleration. We present the observation of well-collimated proton beams with a divergence as low as 1-2 degree and energies up to 8 MeV with a laser pulse of 0.4 J and 30 fs duration irradiating ultrathin DLC foils. The divergence strongly depends on the focal size of the laser and the highest energetic protons are generated even with a moderate laser intensity as low as 4?10^18 W/cm2. Parallel measurement of laser transmission and reflection allows us to determine the laser absorption to the target. We find a strong correlation to the maximum proton energy which may allow a better understanding of the laser absorption into electrons which is of great interest for fast ignition. Moreover, the remarkable ion bunch characteristics enabled us to irradiate living cells with a single shot dose of up to 7 Gray in one nanosecond for the first time, utilizing MPQ's table top ATLAS laser system. Although many issues still remain to be solved, our demonstration of the feasibility of a very compact laser-driven beam line for proton acceleration, transport and delivery bolsters future applications such as laser driven hadron therapy.

8779-57, Session 12

Post-acceleration of laser-driven protons with a compact high field linac

Stefano Sinigardi, Francesco Rossi, Istituto Nazionale di Fisica Nucleare (Italy) and Univ. degli Studi di Bologna (Italy); Pasquale Londrillo, Istituto Nazionale di Fisica Nucleare (Italy); Giorgio Turchetti, Istituto Nazionale di Fisica Nucleare (Italy) and Univ. degli Studi di Bologna (Italy); Paul R. Bolton, Japan Atomic Energy Agency (Japan)

We present a start to end 3D numerical simulation of a hybrid scheme for the acceleration of protons. The scheme is based on a first stage acceleration by 300 TW laser, followed by transport line with a solenoid, and then a post-acceleration section in a compact linac. We show in simulation that for laser accelerated proton bunches selected at ~30 MeV injection energy, it is possible to obtain a high quality monochromatic beam of 60 MeV with intensity above the threshold of interest for medical use.

In the present day experiments with solid targets, the TNSA mechanism describes accelerated bunches with an exponential energy spectrum up to a cut-off value typically below ~60 MeV and wide angular distribution. At the cut-off energy, the number of protons to be collimated and post-accelerated in a hybrid scheme are still too low.

We investigate laser-plasma acceleration with optimum design of target configurations to improve the quality and number of the injected protons at ~30 MeV in order to assure efficient post-acceleration in the hybrid scheme. The results are obtained with 3D PIC simulations using a code where optical acceleration with overdense or near-critical density targets, transport for injection and post-acceleration in a linac, can all be investigated in an integrated framework. The high intensity I=?10?^21W/cm2 experiments at Nara and lower intensity I<?10?^20W/cm2 experiments at Frascati are taken as a reference benchmarks for our virtual laboratory.

If experimentally confirmed, a hybrid scheme could be the core of a medium sized infrastructure for medical research, capable of producing protons for therapy and x-rays for diagnosis, which complements the development of all optical systems.

8779-58, Session 12

Recent advances in ion acceleration from ultrathin foils with Petawatt pulses

Marco Borghesi, Queen's Univ. Belfast (United Kingdom)

The extreme conditions reached during the interaction of an ultra-intense laser pulse with matter can lead, if suitably controlled, to the rapid acceleration of beams of ions with unique properties. The study of these laser-initiated acceleration mechanisms, and the characterization and optimization of the ion beams produced, have been, over the past decade, one of the most active and fruitful areas of high-field science. Key to this interest are the ultra-compact spatial scale of the accelerator and the fact that the properties of laser-driven ion beams are, under several respects, markedly different from those of "conventional" accelerator beams. A particularly high-profile application of the high-current ion beams (proton and heavy ions) is in particle therapy of cancer, which has acted as an important motivation for a significant international research effort, including a number of large projects.

Among a number of other stringent requirements that a laser-driven source should satisfy, a necessary condition for application to cancer therapy of deep-seated tumours is the provision of high-flux proton bunches with energies in the 150-250 MeV range. For this purpose, several acceleration routes are currently investigated by researchers worldwide. Among these, Particle in Cell simulations have highlighted as particularly promising the Light Sail scenario of Radiation Pressure Acceleration, in which the ions within the irradiated portion of an ultrathin foil is detached and propelled by the Radiation pressure as a compact, neutralized layer.

In a number of campaigns at RAL we have investigated acceleration from ultrathin foils, with the aim to identify features related to Radiation Pressure Acceleration. A recent publication [1] has highlighted the emergence of narrow band peaks in the ion spectra when the thickness of the irradiated target was reduced below 0.5-1 µm, down to 50 nm thickness. The target employed were metallic (Cu and Al), and spectral bunching was observed in the contaminant species, but not in the bulk target component. This was consistent with scenarios of multispecies ion acceleration highlighted by recent Particle in Cell simulations, where the Light Sail drive of the heavier ion species goes unstable, but provides a neutralizing electron background which is beneficial for the bunched acceleration of the lighter ion species [2]. Furthermore, the acceleration appears to take place in a hybrid regime, where LS RPA coexists with Target Normal Sheath Acceleration [3]. More recent measurements will also be reported, which have highlighted the dependence of the accelerated ions energies on fluence rather than on intensity, as predicted by analytical scalings for LS acceleration, and on the atomic number of the bulk target ions. Based on these results and current understanding of LS RPA, prospects and challenges towards energies of relevance to medical applications will be discussed.

8779-59, Session 12

Laser-ion acceleration from transparent overdense plasmas at the Texas Petawatt

ishay pomerantz, Joel Blakeney, Gilliss Dyer, Lindsay Fuller, Erhard Gaul, Alexander R Meadows, Chunhua Wang, The University of Texas at Austin (United States); Donald C Gautier, Rahul Shah, Daniel Jung, Juan C Fernandez, Los Alamos National Laboratory (United States); Todd Ditmire, Manuel B Hegelich, The University of Texas at Austin (United States)

A steady increase of on-target laser intensity with also increasing pulse contrast is leading to light-matter interactions of extreme laser fields with matter in new physics regimes. At the Texas Petawatt laser (TPW) we have realized interactions in the transparent-overdense regime, which is reached by interacting a highly relativistic, ultra-high contrast laser pulse with a solid density ultrathin target. The extreme fields in the laser focus are turning the overdense, opaque target transparent to the laser by the relativistic mass increase of the electrons. Thus, the interaction becomes volumetric, increasing the energy coupling from laser to plasma.

Using plasma mirrors to increase the on-target contrast ratio, we demonstrated generation of over 60 MeV proton beams with pulse energies not exceeding 40 J (on target). We further applied these beams to generate neutrons using a Be converter, and demonstrated yields of over 109 neutrons per shot.

I will discuss these results and the plans for an extensive campaign to improve the TPW contrast ratio planned for 2013. Following this campaign we expect ion beam energies to scale over 150 MeV/amu. The shown results now approach the limits set by many applications from ICF diagnostics over ion fast ignition to medical physics.

8779-63, Session 12

ELIMED: a new hadron therapy concept based on laser driven ion beams

G. A. P. Cirrone, Istituto Nazionale di Fisica Nucleare (Italy) and ELI-Beamlines Project (Czech Republic); Daniele Margarone, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Maggiore M., Istituto Nazionale di Fisica Nucleare (Italy) and ELI-Beamlines Project (Czech Republic); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic); G. Cuttone, Istituto Nazionale di Fisica Nucleare (Italy); Francesco Schillaci, Istituto Nazionale di Fisica Nucleare (Italy) and ELI-Beamlines Project (Czech Republic); V. Scuderi, ELI-Beamlines Project (Czech Republic) and INFN-LNS (Italy); A. Tramontana, Istituto Nazionale di Fisica Nucleare (Italy); Jan Prokupek, Andriy Velyhan, Institute of Physics of the ASCR, v.v.i. (Czech Republic); S. B. Jia, Lorenzo Torrisi, Santo Gammino, Istituto Nazionale di Fisica Nucleare (Italy); Marcella Renis, Univ. degli Studi di Catania (Italy); Lorenzo Manti, Univ. Federico II (Italy); Francesco Paolo Romano, INFN-LNS (Italy); Jiri Limpouch, Jan Psikal, Czech Technical Univ. in Prague (Czech Republic); Marco Borghesi, Queen's Univ. Belfast (United Kingdom); Stepan S. Bulanov, Univ. of California/Berkeley (United States); Sergei Bulanov, Japan Atomic Energy Agency (Japan); Massimo Carpinelli, INFN, Univ. of Sassasi (Italy)

Laser accelerated proton beams have been proposed to be used in different research fields. A great interest has risen for the potential replacement of conventional accelerating machines with laser-based accelerators, and in particular for the development of new concepts of more compact and cheaper hadrontherapy centers.

In this context the ELIMED (ELI MEDical applications) research project has been launched by INFN-LNS and ASCR-FZU researchers within the pan-European ELI-Beamlines facility framework. The ELIMED project aims to demonstrate the potential clinical applicability of optically accelerated proton beams and to realize a laser-accelerated ion transport beamline for multidisciplinary user applications. In this

picture the eye melanoma (Uveal melanoma) (normally treated with 62 MeV proton beams produced by standard accelerators) will be considered as a model system to demonstrate the potential clinical use of laser-driven protons in hadrontherapy, especially because of the limited constraints in terms of proton energy and irradiation geometry for this particular tumour treatment.

Several challenges, starting from laser-target interaction and beam transport development up to dosimetry and radiobiology, need to be overcome in order to reach the ELIMED final goals. A crucial role will be played by the final design and realization of a transport beamline capable to provide ion beams with proper characteristics in terms of energy spectrum and angular distribution which will allow performing dosimetric tests and biological cell irradiation. A first prototype of transport beamline has been already designed and some transport elements are under construction in order to perform a first experimental test with the TARANIS laser system by the end of 2013.

A wide international collaboration among specialists of different disciplines like Physics, Biology, Chemistry, Medicine and medical doctors coming from Europe, Japan, and the US is growing up around the ELIMED project with the aim to work on the conceptual design, technical and experimental realization of this core beamline of the ELI Beamlines facility.

8779-60, Session 13

Microstructured snow target for quasi-monochromatic high energy proton acceleration

Arie Zigler, The Hebrew Univ. of Jerusalem (Israel)

Proton acceleration by the interaction of an ultra high intensity laser beam with matter has several wide prospective applications. Previously proposed schemes of laser based acceleration of protons, require PW laser systems for achieving the 150MeV proton energy levels applicable for cancer treatment. Here we experimentally demonstrate quasi-monenergetic 25MeV proton bunches accelerated by the interaction of a 5TW ultra short laser pulse with a microstructured snow target. This significantly increased proton energy over the traditional approach is the result of localized enhancement of the laser field intensity near the microstructured tip. The localized field enhancement amplifies the charge separation in the plasma, leading to improved acceleration of the protons for the same laser power. Our microstructured snow scheme also relaxes the requirements of high contrast ratio of the laser system.

Scaling of the experimentally obtained proton energy, corroborated by our detailed 2D PIC simulations of the interaction process, result in the potential of reaching the desired 150MeV proton energy at a modest lasers power of 0.1PW

8779-62, Session 13

Measurements and modelisation of the response function of Imaging Plates to protons, electrons, photons and alpha particles

Thomas Bonnet, Maxime Comet, David Denis-Petit, Franck Gobet, Fazia Hannachi, Medhi Tarisien, Maud Versteegen, Marie-Madeleine Aleonard, Institut National de Physique Nucléaire et de Physique des Particules (France)

Imaging plates are ionizing-particle sensitive detectors well-suited for the characterization of laser-accelerated particle beams. They were originally developed for imaging techniques for medical applications. They are now used in many experiments in which a good spatial resolution (50 µm), a good sensitivity (a few particles can be detected) or a detector insensitive to the EM fields accompanying a laser shot are needed. Quantitative experimental data are still needed in order to relate the measured signal, given in unit of photostimulated light (PSL) to the absolute number of particles passing through the detector.

Our group measured the response functions in PSL per proton using monoenergetic protons delivered by the AIFIRA accelerator with energies ranging from 0.6 MeV to 3.2 MeV. This talk will present our experimental results for the calibration of three types of Fuji IPs (TR, MS, SR) with AIFIRA proton beam. Data with radioactive sources allowing the calibration to electrons, photons and alpha particles will also be described. The problem of “fading” will be addressed and a method to measure and correct its effects on data will be proposed. A modelisation with Monte Carlo simulations has also been performed to extend the energy range of the calibration. Depending on the ionizing particle different processes have been taken into account. Our experimental results and our modelisation will be discussed. A comparison with previous works will be made in the talk. Finally a protocol will be proposed to calibrate the set IP/scanner at each new campaign of measurements using a 90Sr radioactive source.

Conference 8779C: Harnessing Relativistic Plasma Waves as Novel Radiation Sources from Terahertz to X-rays and Beyond III

Wednesday - Thursday 17–18 April 2013

Part of Proceedings of SPIE Vol. 8779 Laser Acceleration of Electrons, Protons, and Ions II; and Medical Applications of Laser-Generated Beams of Particles II; and Harnessing Relativistic Plasma Waves III

8779-65, Session 15

Generation of electron beam and betatron x-ray sources from laser-driven atomic clusters *(Invited Paper)*

Liming Chen, Institute of Physics (China)

Because synchrotron x-ray sources have large cost and experimental footprint, relatively long pulse structure and synchronization difficulty in sub-picosecond pump-probe diagnostics, new compact x-ray sources are being anticipated. Hard x-ray sources from femtosecond laser-produced plasmas, including the betatron x-rays which generated during electron wake-field acceleration, have compact sizes, fs pulse duration and fs pump-probe capability, making it potential for wide use in material and biological sciences. However, the flux of betatron x-ray source is limited by the charge and oscillation amplitude of accelerated electrons in gas target, even using ultra-intense laser pulses. In a recent experimental studies, we obtained that an ultra-bright betatron x rays have been generated using a clustering gas jet target irradiated with a small size laser (~ 3 TW). A ten-fold enhancement compared to the flux produced using a gas target is achieved. We suggest that the increased betatron x-ray photon production is due to the existence of clusters in the gas, which results in increased total electron charge trapped for acceleration and much larger wiggling amplitudes during the acceleration. This observation opens a new window to produce applicable betatron flux using small size laser facility.

8779-66, Session 15

Betatron x-ray production in mixed gases *(Invited Paper)*

Felicie Albert, Bradley B. Pollock, Joseph E. Ralph, Lawrence Livermore National Lab. (United States); Kenneth A. Marsh, Christopher E. Clayton, Jessica Shaw, Chandrashekhar J. Joshi, Siegfried H. Glenzer, Univ. of California, Los Angeles (United States)

Betatron x-rays with photon energies larger than 20 keV have been observed from a GeV-class laser-plasma accelerator. The experiment was performed using the 200 TW Callisto laser system at LLNL to produce and simultaneously observe GeV-class electron beams and keV Betatron x-rays. The laser was focused with two different optics (F/8 and F/20) into various gas cells with sizes ranging from 3 to 8 mm, and containing mixed gases (He, N, O2, Ar, Ne) to accelerate large amounts of charge in the ionization induced trapping regime. KeV betatron x-rays were observed simultaneously with electron beams for various concentrations of gases on two large image plates. Electron spectra were measured on these large image plates with the two-screen method (to measure both the electron beam energy and deflection out of the plasma) after being deflected by a 0.4 Tesla magnet spectrometer containing one or two 21 cm long magnets. In addition to the detection of electrons and x-rays, several diagnostics were implemented. First, a modified Mach-Zehnder interferometer permitted the electron density measurement for each laser shot. Then, both forward imaging and spectrometry of the laser at the exit of the plasma allowed us to confirm self-guiding of the laser pulse during the interaction over several mm. Fine structures of the betatron oscillations were also directly observed on the electron spectra and can be benchmarked against a simple analytical model (Runge-Kutta algorithm solving the equation of motion of an electron in the wakefield) as well as against PIC simulations using OSIRIS. This method was used to retrieve the electron injection conditions into the wake as well as the 3-dimensional trajectory of the electrons in the plasma. The theoretical x-ray beam profiles produced by these trajectories where compared with the full experimental beam profile (several milliradians) observed on the image plates. This analysis, combined with spectral and spatial measurements of the produced x-rays suggests an enhancement of the betatron mechanism and x-ray yield in the ionization induced trapping regime of laser-wakefield acceleration.

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

8779-67, Session 16

Longitudinal space charge amplifier *(Invited Paper)*

Evgeny Schneidmiller, Mikhail V. Yurkov, Deutsches Elektronen-Synchrotron (Germany)

Longitudinal space charge driven microbunching instability in electron beam formation systems of X-ray FELs is a recently discovered effect hampering beam instrumentation and FEL operation. We propose to use such an instability for generation of vacuum ultraviolet and X-ray radiation. A typical longitudinal space charge amplifier (LSCA) consists of few amplification cascades (focussing channel plus chicane) with a short undulator behind the last cascade. If the amplifier starts up from shot noise, the amplified density modulation has a wide band, on the order of unity. The bandwidth of the radiation within the central cone is given by inverse number of undulator periods. LSCA can be used as a cheap addition to the existing or planned short-wavelength FELs. In particular, it can produce the second color for a pump-probe experiment. It is also possible to generate attosecond pulses in the VUV and X-ray regimes. Some user experiments can profit from a relatively large bandwidth of the radiation, and this is easy to obtain in LSCA scheme.

Finally, since the amplification mechanism is broadband and robust, LSCA can be an alternative to a SASE FEL in the case of using laser-plasma accelerators as drivers of light sources.

8779-68, Session 16

Generation of attosecond soft x-ray pulses in a longitudinal space charge amplifier *(Invited Paper)*

Mikhail V. Yurkov, Evgeny Schneidmiller, Martin Dohlus, Deutsches Elektronen-Synchrotron (Germany)

A longitudinal space charge amplifier (LSCA), operating in soft x-ray regime, was recently proposed. Such an amplifier consists of a few amplification cascades (focusing channel and chicane) and a short radiator undulator in the end. Broadband nature of LSCA supports generation of few-cycle pulses as well as wavelength compression. In this paper we consider an application of these properties of LSCA for generation of attosecond x-ray pulses. It is shown that a compact and cheap addition to the soft x-ray free electron laser facility FLASH would allow to generate 60 attosecond (FWHM) long x-ray pulses with the peak power at 100 MW level and a contrast above 98%.

8779-69, Session 16

Longitudinal space charge amplifier driven by a laser-plasma accelerator *(Invited Paper)*

Martin Dohlus, Evgeny Schneidmiller, Mikhail V. Yurkov, Florian J. Grüner, Deutsches Elektronen-Synchrotron (Germany)

A longitudinal space charge amplifier (LSCA), operating in VUV anmd soft x-ray regime, was recently proposed. Such an amplifier consists of a few amplification cascades (focusing channel and chicane) and a short radiator undulator in the end. The amplification mechanism is broadband and robust, it is practically insensitive to energy chirp and orbit jitter. Therefore, an LSCA can be considered as an alternative to a SASE FEL in the case of using laser-plasma accelerators as drivers of light sources. In this report we study generation of VUV radiation (below 100 nm) in an LSCA driven by a laser-plasma accelerator with the energy of 300 MeV.

8779-70, Session 17

Picosecond narrow bandwidth X-ray pulses from a Laser-Thomson-Backscattering source *(Invited Paper)*

Axel Jochmann, Arie Irman, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

Intense ultra-short hard X-ray pulses can serve as a novel tool for structural analysis of complex systems with unprecedented temporal and spatial resolution. With the simultaneous availability of a high power short-pulse laser system it provides unique opportunities for a number of subsequent research steps at the forefront of relativistic light-matter interactions. At HZDR we demonstrated the generation of such a light source (PHOENIX) by colliding picosecond electron bunches from the ELBE linear accelerator with counter-propagating femtosecond laser pulses from the 150 TW Draco Ti:Sapphire laser system. The generated narrowband X-rays are highly collimated and can be reliably adjusted from 5.5 to 23.5 keV by tuning the electron energy (24 MeV to 30 MeV) and the laser intensity. Ensuring the spatial-temporal overlap at the interaction point and suppressing the Bremsstrahlung background we have achieved a signal to noise ratio of greater than 300. Together with the use of an X-ray camera to record the spectrum (resolution of 250 eV FWHM) we were able to resolve the angular-energy correlation and to study the influence of the beam emittance on the observed bandwidth. Besides the use of the thermionic gun we also collided electron bunches generated from an SRF photo-injector. Here we detected a few orders of magnitude higher Bremsstrahlung background from the machine dark current. By carefully subtracting the background we extracted the X-ray spectrum whose peak overlaps with the one from the thermionic as expected for the same electron energy.

8779-71, Session 17

Single-cycle pulse generation by Thomson-scattering in the MIR to X-Ray spectral ranges *(Invited Paper)*

Zoltán Tibai, György Tóth, József A. Fülöp, János Hebling, Univ. of Pécs (Hungary)

The generation of waveform-controlled single- or few-cycle electromagnetic pulses down to the VUV or X-ray wavelengths is of considerable interest for applications in spectroscopy of ultrafast processes. However, the presently available ultrafast sources in these wavelength ranges deliver multi-cycle pulses. Contrary to the optical range, intense waveform-controlled single- or few-cycle pulses are easily available in the THz range. Here we propose to use Thomson scattering of intense THz pulses from ultra-thin relativistic electron sheets for the generation of waveform-controlled single- or few-cycle pulses in the MIR down to the EUV regimes.

By numerical calculations we investigated both the generation of ultra-thin electron bunches as well as the Thomson scattering process. Starting with a 1.8 ps long 1 nC, 61 MeV electron bunch delivered by a conventional rf accelerator, the electrons were passing through a single-period undulator with co-propagating laser radiation of 1.3 µm wavelength and 3.9 TW peak power, which lead to the formation of microbunches with 0.7 pC charge and down to 22 nm longitudinal size. Coherent Thomson scattering of a counter-propagating single-cycle THz pulse with 0.1 THz mean frequency and 10 MV/cm focused peak electric field lead to the generation of a single-cycle EUV pulse with around 65 nm wavelength, 128 pJ energy, and excellent far-field beam profile. In both cases the pulse waveform is preserved to a good accuracy, and the method is also suitable to generate few-cycle shaped pulses down to 50 nm wavelengths.

8779-72, Session 17

Nonlinear Thompson/Compton scattering from GeV laser-wakefield accelerated electron bunches *(Invited Paper)*

Joana L. Martins, Marija Vranic, Jorge M. Vieira, Ricardo A. Fonseca, Luis O. Silva, Univ. Técnica de Lisboa (Portugal)

Laser-wakefield accelerators (LWFA) have been proven capable of delivering electron bunches with energies in excess of 1 GeV. By colliding highly energetic electron bunches such as the ones produced in these accelerators with ultra-intense laser pulses, radiation can be produced due to nonlinear Thompson/Compton scattering, a process well known from the literature.

In this work, we explore a scheme where laser wakefield accelerated GeV electron bunches are made to collide with ultra-intense laser pulses with intensities on the order of 10^21 W/cm^2. Under these conditions, it is possible to enter a regime where the radiation damping of the electrons through nonlinear Thompson/Compton scattering can lead to significant energy loss of the electron bunch. Intensities of this level are already available at some laser laboratories and even greater intensities will be attainable at the ELI facility. With the increasing laser intensities available, assessing the radiation damping effects and understanding the transition to QED regimes will become increasingly important. It is also interesting to explore the potential of nonlinear Thompson/Compton scattering as an X-ray source in these radiation damping dominated regimes.

In this work, the radiation emitted by the bunch electrons during the interaction with the laser pulse will be explored in detail through 3D particle-in-cell (PIC) numerical simulations (including radiation damping) performed with the OSIRIS 2.0 framework. Trajectories from these simulations will be post-processed to obtain the emitted radiation spectrum and features such as maximum photon energy and the spectrum shape will be analyzed.

8779-73, Session 18

Radiation reaction effects on the motion of an electron in an intense laser pulse *(Invited Paper)*

Yevgen Kravets, Adam Noble, Dino A. Jaroszynski, Univ. of Strathclyde (United Kingdom)

The classical theory of radiation reaction reveals problems such as “runaway solutions” and violation of causality. Over the years many questions have arisen regarding the validity of existing approaches to these problems. This work explores an alternative treatment of the motion of a radiating electron, based on an equation first proposed by Ford and O’Connell. A general condition is found for solutions of this equation to deviate from those of the traditional formulation, and is demonstrated for an electron in an intense laser field.

8779-74, Session 18

A new approach to radiation reaction in charged fluids *(Invited Paper)*

David A. Burton, Lancaster Univ. (United Kingdom)

Contemporary developments in ultra-high intensity laser-plasma science have driven the recent surge of interest in relativistic plasmas in strong-field regimes where the electromagnetic self-force plays a significant role. A new kinetic theory of radiation reaction (arXiv:1210.5467) is used to induce a new, fully covariant, warm fluid description of a radiating relativistic plasma and an investigation of its wave solutions is undertaken.

8779-75, Session 19

700 micro Joule THz pulses from a laser-driven particle accelerator *(Invited Paper)*

Amrutha Gopal, Friedrich-Schiller-Univ. Jena (Germany); Torsten May, Institut für Photonische Technologien e.V. (Germany); Pushkar Singh, Sven Herzer, Wolfgang Ziegler, Gerhard G. Paulus, Albrecht Schmidt, Andreas Reinhard, Friedrich-Schiller-Univ. Jena (Germany); Ulrich Dillner, Hans-Georg Meyer, Institut für Photonische Technologien e.V. (Germany); Anupam Karmakar, Dirk Broemmel, Paul Gibbon, Forschungszentrum Jülich GmbH (Germany)

Terahertz radiation (T-rays) bridging the gap between photonics and electronics is one of the most active fields of current research. Due to their wide spread applications ranging from imaging, material science to nonlinear optics, THz radiation attracts huge interest and the search for more powerful and compact source is growing rapidly. Here we report a laser-plasma-driven source of T-rays with the highest pulse energy ever recorded in a laboratory. T-rays are emitted from the rear surface of a solid target in the non-collinear direction at incident laser intensities ~ 1019 W/cm2. Pulse energy measurements detected T-ray pulses with peak energies 700 mJ. Temporal measurements using a single-shot electro-optic method showed the presence of sub-picosecond T-ray pulses with 570 fs duration, thus rendering the peak-power of the source higher even than that of state-of-the-art synchrotrons. A conversion efficiency of higher than 10?3 and a peak power above a GW makes it the most efficient compact and powerful THz source known today. Spectral analysis revealed the presences of frequencies ranging from 0.1-133 THz, while most of the energy is localised in the low frequency region. The dependence of T-ray yield on incident laser energy is linear and shows no tendencies of saturation. The spatial distribution of the recorded T-rays indicates that most of the T-rays are emitted in the non-collinear direction from the rear-surface of a solid target and the contribution in the forward direction is very small. 2D particle-in-cell simulations show the presence of transient current at the target rear surface.

8779-76, Session 19

CPA Raman Compton transition: experimental demonstration of ultrashort laser pulse amplification in plasma in the transition regime *(Invited Paper)*

Dino A. Jaroszynski, Gregory Vieux, Xue Yang, Enrico Brunetti, Bernhard Ersfeld, Univ. of Strathclyde (United Kingdom); John P. Farmer, Univ. of Strathclyde (Germany); R. Isaac, Gaurav Raj, Mark Wiggins, Gregor H. Welsh, Silvia Cipiccia, David W. Grant, Univ. of Strathclyde (United Kingdom); M. W. Hur, UNIST (Korea, Republic of); Nuno R. C. Lemos, Univ. Técnica de Lisboa (Portugal); Jorge Miranda Dias, Institute of Systems and Robotics (Portugal)

Raman amplification in plasma has been proposed as a new way of producing high power coherent radiation and also a means of compressing a high energy laser pulse to ultra-short duration, and a way of combining several high power laser beams. In contrast to conventional solid-state material used as laser amplifiers and parametric amplifying media, plasma has the advantage in that it is already broken down into its constituent parts so cannot suffer damage. This implies that plasma should be a convenient medium to reach very high powers, exceeding current laser technology. Furthermore, unlike conventional media, plasma is very flexible in that it can be used to amplify, compress and combine laser beams, and it is not restricted to a particular region of the electromagnetic spectrum. In this talk we will present results of an experimental and theoretical programme to investigate Raman amplification and also study the transition to the Compton regime where the ponderomotive force of the pump and probe (seed) lasers is much larger than the internal plasma forces. We will show how broad bandwidth amplification occurs when the pump laser beam is chirped, which has the effect of causing amplification of each Fourier component of the probe (seed) pulse at a different position in the plasma medium. This spatio-temporal distribution of the gain allows well controlled amplification. The experiments that will be presented in the talk have been carried out at the University of Strathclyde using a CPA Ti:sapphire laser to demonstrate chirped pulse Raman amplification and the transition to the Compton regime, and at the Rutherford Appleton Laboratory, using a 150 J glass laser, where gains in excess of 107 have been measured with efficiencies of the order of 1%.

8779-77, Session 20

Kinetic simulations of intense light pulses generated by Brillouin backscattering in laser-plasma interaction *(Invited Paper)*

Caterina Riconda, Ecole Polytechnique/IZEST International Ctr. for Zettawatt-Exawatt Science and Technology Stefan Weber, Julien Fuchs, Livia Lancia, J. R. Marques, Ecole Polytechnique (France); Gérard A. Mourou, Ecole Polytechnique/IZEST International Ctr. for Zettawatt-Exawatt Science and Technology (France)

Due to their extremely high damage threshold, plasmas can sustain much higher light intensities than conventional solid state optical materials. Because of this, lately much attention has been devoted to the possibility of using parametric instabilities in plasmas to generate very intense light pulses in a low-cost way.

Although short-pulse amplification based on the Raman approach has been successful[1] and goes back a long time[2], it is shown that using Brillouin the so called strong-coupling regime (sc-SBS) has several advantages [3] and is very well suited to amplify and compress laser seed pulses on short distances to very high intensities. We present here recent multidimensional kinetic simulations that show the feasibility of achieving amplified light pulses of up to 1018W=cm2. We also show that shaping the plasma and extending the laser beams diameter allows for high efficiency of the process while minimizing other unwanted plasma processes. Moreover, contrary to what was traditionally thought, this scheme is able to amplify pulses of extremely short duration. Although seed amplification via sc-SBS has already been shown experimentally[4], these results suggest further experimental exploration, in order to improve the energy transfer.

References

[1] J. Ren, W. Cheng, S. Li & S. Suckewer Nature Phys. 3, 732-736 (2007).

[2] M. Maier, W. Kaiser & J.A. Giordmaine, Phys. Rev. Lett. 17, 1275-1277 (1966).

[3] A.A. Andreev, C. Riconda, V.T. Tikhonchuk & S. Weber, Phys. Plasmas 13, 053110 (2006).

[4] L. Lancia et al. Phys. Rev. Lett. 104, 025001 (2010).

8779-78, Session 20

Extension of the aPIC model for simulation of Raman amplification experiments *(Invited Paper)*

John P Farmer, Institut für Theoretische Physik 1, Heinrich Heine Universität, Düsseldorf (Germany); MinSup Hur, UNIST (Korea, Republic of); Bernhard Ersfeld, Gregory Vieux, Dino A Jaroszynski, SUPA and University of Strathclyde (United Kingdom)

Raman amplification in plasma is a potential method for the creation of ultrashort, ultraintense laser pulses, which have applications across science and engineering disciplines, for example as drivers for wakefield acceleration, or for use in fast ignition schemes for inertial confinement fusion.

While PIC simulations capture most of the relevant physics of the interaction, simulation of Raman amplification can be computationally intensive, as the short wavelength of the excited plasma wave requires high resolution, while phenomena such as wavebreaking and Landau damping require a large number of particles per cell.

The aPIC code was created to allow simulation of the Raman interaction with a significantly lower computational overhead. We here present the continued development of the aPIC code to allow simulation of experimentally relevant regimes, including chirped laser pulses and dispersion of the laser pulses. Dispersion is especially important to capture the physics of guiding and focussing, which play a significant role in the experimental work carried out at Strathclyde.

Conference 8780A: High-Power, High-Energy, and High-Intensity Laser Technology

Monday - Wednesday 15–17 April 2013

Part of Proceedings of SPIE Vol. 8780 High-Power, High-Energy, and High-Intensity Laser Technology; and Research Using Extreme Light: Entering New Frontiers with Petawatt-Class Lasers

8780-1, Session 1

Orion: a commissioned user facility *(Invited Paper)*

Paul A. Treadwell, Peter M. Allan, Nicholas Cann, Colin N. Danson, Stuart J. Duffield, Stephen P. Elsmere, Ray D. Edwards, David A. Egan, Mark Girling, Edward Gumbrell, Ewan J. Harvey, Matthew P. Hill, David I. Hillier, David J. Hoarty, Lauren Hobbs, Nicholas W. Hopps, Dianne Hussey, Kevin Oades, Steven James, Michael J. Norman, James Palmer, Stefan Parker, David N. Winter, Thomas H. Bett, AWE plc (United Kingdom)

The Orion Laser Facility at AWE in the UK consists of ten nanosecond beam lines and two sub-picosecond beam lines. The nanosecond beam lines each nominally deliver 500 J at 351 nm in a 1 ns square temporal profile, but can also deliver a user-definable temporal profile with durations between 0.1 ns and 5 ns. The sub-picosecond beam lines each nominally deliver 500 J at 1053 nm in a 500 fs pulse, with a peak irradiance of greater than 1021 W/cm2. One of the sub-picosecond beam lines can also be frequency-converted to deliver 100 J at 527 nm in a 500 fs pulse, although this is at half the aperture of the 1053 nm beam.

Commissioning of all twelve beam lines has been completed, including the 527 nm sub-picosecond option. An overview of the design of the Orion beam lines will be presented, along with a summary of the commissioning and subsequent performance data. We will discuss issues that arose during the commissioning process, such as the effect of wavefront error on the compression of pulses in the sub-picosecond beam lines, and the difficulty in accurately diagnosing the duration of the sub-picosecond pulses. The improvement in pulse contrast from using the 527 nm option will also be illustrated.

The design of Orion was underwritten by running various computer simulations of the beam lines. Work is now underway to validate these simulations against real system data, with the aim of creating predictive models of beam line performance. These predictive models will enable the user's experimental requirements to be critically assessed ahead of time, and will ultimately be used to determine key system settings and parameters. For example, for the nanosecond beam lines the required energy and temporal profile of the pulse in the pre-amplifier can be accurately predicted to obtain the user-defined energy and temporal profile on target.

The facility is now conducting high energy density physics experiments. A capability experiment has already been conducted that demonstrates that Orion can generate plasmas at several million Kelvin and several times solid density. Various target diagnostics were commissioned for the experiment, and more are currently in the process of being commissioned. From March 2013 15% of the facility operating time will be given over to external academic users in addition to collaborative experiments with AWE scientists.

8780-2, Session 1

Recent developments on the Vulcan High Power Laser Facility *(Invited Paper)*

Ian Musgrave, Alexis Boyle, Robert J. Clarke, Robert Heathcote, Marco Galimberti, David Neely, Margaret M. Notley, Bryn T. Parry, Waseem Shaikh, Trevor B. Winstone, David A. Pepler, Andrew K. Kidd, Cristina Hernandez-Gomez, John L. Collier, Rutherford Appleton Lab. (United Kingdom)

The Petawatt target area of the Vulcan laser has been operational for 10 years and in that time there have been over 2,500 high energy shots into the target area. In this paper we will report on the recent refurbishment of the laser system that included replacing the large aperture optics in the compressor and the interaction chamber. We will also discuss the developments that we have made to the laser and our future plans for the system. These will include the enhancement to our laser diagnostic provision by introducing an additional laser diagnostics line, the laser contrast improvement by the addition of a picosecond OPCPA stage and the development of off harmonic-probes.

In this paper we present the results of a recent upgrade to the Vulcan Petawatt laser facility front-end to improve the nanosecond amplified spontaneous emission (ASE) contrast by greater than 2 orders of magnitude. The upgraded front end introduces an single picosecond stretch and then an OPA stage to generate a clean high energy seed pulse that is then injected into the Vulcan laser. The picosecond OPA generates pulses that have >100?J of energy these pulses are then injected into the existing nanosecond amplification system. With this increased seed energy we are able to reduce the small signal gain required from the ns OPA and thereby reduce the ASE on the ns timescales.

Optical probes are often used to diagnose the laser plasma interactions in the Vulcan Petawatt facility revealing information about the internal plasma parameters such as absolute density, density gradients, temperature and velocity gradients. These interactions are often very complex and result in light that is scattered and generated in a number of wavelengths and directions. Currently these probes are typically provided using a mirror to pick-off a small portion of the main interaction beam and then modifying it to form a probe beam. Measurements of the scatted spectrum shows that there is a significant amount of the fundamental beam scattered and generation of the second harmonic. There is also a continuum that extends from 700nm to the laser wavelength which is peaked at 850-900nm. Other measurements have shown that there is also significant generation at the 3rd and 4th harmonics. In this paper we will discuss how the pulse will be generated and synchronised to the Vulcan laser. The scheme for amplifying the pulse to the required energy will be presented. We will also discuss our scheme for delivering it to the interaction and how it will be diagnosed.

8780-3, Session 1

Development and application of the Diagnostic Improvement and Verification Apparatus (DIVA) at the Z-Backlighter Laser Facility at Sandia National Laboratories *(Invited Paper)*

Mark W. Kimmel, Matthias Geissel, Patrick K. Rambo, Jens Schwarz, Sandia National Labs. (United States); James MacArthur, John Stahoviak, Sandia Staffing Alliance (United States); John L. Porter, Sandia National Labs. (United States)

The Z-Backlighter Laser Facility at Sandia National Laboratories provides X-ray radiography for the adjacent Z-accelerator. In order to develop and test the latest generation of X-ray diagnostics employed on the Z-machine, we have developed the DIVA testbed. The DIVA laser source consists of an ultra-stable DPSS Nd:YAG regenerative amplifier, seeded by a source with pulse shaping capability provided by a programmable Arbitrary Waveform Generator. Amplification of this seed pulse is accomplished by flashlamp-pumped Nd:YAG and Nd:Silicate Glass rod amplifiers in apertures ranging from 6mm to 64mm diameter, used in single and double pass configurations. Maximum output energy at 1.064 micron wavelength is greater than 50J/ pulse with 12 minute pulse repetition time. Waveform tuning of the seed pulse has been used to create amplified pulses with temporal profiles ranging from 300ps to more than 5ns, with single and multiple pulse bursts. Second Harmonic Generation efficiencies of greater than 70 percent have been achieved. A full cadre of diagnostics is used to monitor and record laser pulse parameters. Pulses are focused into the DIVA target chamber with an f/10 focal geometry. Focal spot sizes of

sub-10 micron have been recorded.

DIVA has been used to characterize and calibrate X-ray diagnostics such as the "Streak Polar Instrument for the Detection of Energetic Radiation (SPIDER)" for the National Ignition Campaign and high speed diodes at photon energies of 4.7 keV. The latest campaign involved ultrafast sequential framing of X-ray images with nanosecond interframe times, during which DIVA's multi-pulse capability was applied to illuminate specific frames. Such varied temporal x-ray measurements leverage the DIVA laser combination of adjustable temporal waveform and high energy capabilities in order to provide a unique x-ray diagnostic characterization.

8780-4, Session 1

PEnELOPE: a high peak-power diode-pumped laser system for laser-plasma experiments *(Invited Paper)*

Mathias Siebold, Markus Loeser, Fabian Röser, Daniel Albach, Ulrich Schramm, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

With the first demonstration of direct diode-pumped TW lasers with pulse energies of 1J and more a scaling of this approach for use in PW-class laser systems became feasible. The Helmholtz-Centre Dresden-Rossendorf builds a fully diode-pumped Petawatt laser for laser-particle acceleration research. Within the PEnELOPE project (Petawatt, Energy-Efficient Laser for Optical Plasma Experiments) a pulse energy of 150J, a repetition rate of ~1Hz and a pulse duration of 150fs after compression are desired. In order to minimize the required pump peak power and therefore the initial costs a broad-band Ytterbium doped laser material with a long fluorescence lifetime (i.e. Yb:glass or Yb:CaF_2) is chosen. A total pump peak-power of 1.2MW is scheduled assuming a pump pulse duration of 2ms and an envisioned optical-to-optical conversion efficiency of 10% before compression.

Pulses as short as 60fs having an energy of 25nJ are generated in a commercial Yb:KGW oscillator at a center wavelength of 1035 nm. Stretcher and compressor of the CPA-system are designed to expand the pulse duration before amplification to 2ns while exhibiting a hard-clip bandwidth of 50nm in order to achieve high pulse contrast. We utilize highly efficient multilayer dielectric reflection gratings with a line density of 1760 lines per mm, aiming at a compressor throughput of >80%.

The amplifier-chain consists of a regenerative amplifier and 4 subsequent multipass amplifiers. For thermal management we use thin disks at the low-engergy level while at pulse energies of 1J and higher the amplifier design is based on actively cooled multi-slabs. Multipass pumping of the Yb-doped laser material is performed to reduce the re-absorption losses at room temperature.

8780-5, Session 2

DiPOLE: A multi-slab cryogenic diode pumped Yb:YAG amplifier *(Invited Paper)*

Saumyabrata Banerjee, Klaus Ertel, Paul D. Mason, Paul J. Phillips, Justin Greenhalgh, Cristina Hernandez-Gomez, John L. Collier, Rutherford Appleton Lab. (United Kingdom)

The DiPOLE project at the Central Laser Facility (CLF) is aimed at development of a scalable and efficient diode-pumped, gas cooled, cryogenic multi-slab ceramic Yb:YAG amplifier. Optimised designs for an amplifier capable of generating kJ energies in nanosecond pulses at multi-Hz repetition rate have been produced. Development and testing of a scaled-down prototype is near completion. This prototype system aims to demonstrate the viability of the concept and is designed to deliver ns-pulses with 10 J energy at 10 Hz repetition rate and an optical-to-optical (o-o) efficiency of 25%. Preliminary results from a non optimal extraction geometry demonstrated output pulse energies of 10.1 J at 1 Hz and 6.4 J at 10 Hz. Since then a relay-imaging multi-pass extraction architecture with spatial filtering has been installed allowing an increased number of passes and improved output spatial beam quality. In this paper we report the most recent performance results from the DiPOLE prototype amplifier, including the dependence of output energy on the number of passes, operating temperature and the doping uniformity within the amplifier. Results are compared to predictions from a numerical model, including the effect of amplified spontaneous emission (ASE).

8780-6, Session 2

233 mJ 143 Hz Yb:YAG ceramic cryogenic disk laser

Evgeny A. Perevezentsev, Ivan B. Mukhin, Olga L. Vadimova, Ivan I. Kuznetsov, Oleg V. Palashov, Efim A. Khazanov, Institute of Applied Physics (Russian Federation)

Due to effective heat removal and weak self-focusing thin disk lasers are one of the most perspective high capacity and average power lasers. Additional cryogenic cooling leads to increase in absorption spectra as well as heat conductivity [1]. We develop a high power cryogenic disk laser in the IAPRAS (Nizhniy Novgorod, Russia). Our aim is to get sub-joule 100ps pulses at 1kHz repetition rate with the total pump power about 2.5-3 kW at 940 nm wavelength.

At present, we archived about 5 mJ in 50 ns pulse from a master oscillator (MO). Using Active Multipass Cell (AMC) [2] to provide 12 V-passes through the active element of a preamplifier (PA) we reached 54 mJ of energy at 200 Hz repetition rate at 200 mJ pump energy. It corresponds to 25% optical-to-optical efficiency, which is very high for pulsed lasers. The cw regime of pump was tried in PA and up to 30 mJ at 1 kHz was realized. Unfortunately, the average power is limited by LN2 boiling in a cryogenic chamber. To solve this problem, we developed active cooling LN2 system.

The main amplifier has 2 active elements (AE). Maximum pump power is 1.2kW per AE. We archived 100mJ at 200Hz on Yb:YAG disc crystals. [3]. In the next experiment we used ceramic Yb:YAG AE, produced by the Temasek Laboratories @ NTU, AMRC LAB, Nanyang Technological University, Singapore. Experimental investigations of 3 samples with the different grain size showed, that the spectrum behavior at cooling was similar to monocrystals'. We reached 233mJ at 143 Hz in the output with 70ns 30mJ input pulses. In such a way we extracted somewhat half of stored energy. To our knowledge, this output result is the best among all cryogenic pulse Yb:YAG ceramic and Yb:YAG disk monocrystal laser systems. To achieve the planned pulse energy, disk AE will be replaced by Yb:YAG/YAG "sandwiches" to reduce ASE [4]. For the composite AE fabrication we use our own new technique of thermal bonding. The energy stored in the main amplifier in each disk will increase from 180 to 500 mJ. The new geometry of AE may also appreciably improve beam quality, as such a rigid structure will bend much less on cooling to cryogenic temperatures.

References

1. Brown D.C., Bowman R., Kuper J., Lee K.K., Menders J. High average power active-mirror amplifier, Applied Optics, 1986, 25, 612.

2. Joerg Neuhaus, Jochen Kleinbauer, Alexander Killi, Sascha Weiler, Dirk Sutter, and Thomas Dekorsy, Passively mode-locked Yb:YAG thin-disk laser with pulse energies exceeding 13 ?J by use of an active multipass geometry, OPTICS LETTERS / Vol. 33, No. 7 / April 1, 2008

3. I. Mukhin, E. Perevezentsev, A. Vyatkin, O. Vadimova, O. Palashov and E. Khazanov, One kilohertz cryogenic disk laser with high average power, Proc. SPIE 8080, 80800B (2011); doi:10.1117/12.886745

4. D. Kouznetsov and J.-F. Bisson, Role of undoped cap in the scaling of thin-disk lasers, J. Opt. Soc. Am. B, 2008, 25, (3).

8780-7, Session 2

A diode-pumped, cryogenically cooled, femtosecond burst mode CPA laser

Jörg Körner, Joachim Hein, Martin Kahle, Hartmut Liebetrau, Reinhart Seifert, Diethard Klöpfel, Malte C. Kaluza, Friedrich-Schiller-Univ. Jena (Germany)

We present a burst mode laser system based on diode pumped Yb:CaF2 at liquid nitrogen temperature. The intention of this work is to deliver high peak power ultra short pulses up to the terawatt level at a moderate average power but higher efficiency as the typical low repetition rate amplifiers. To achieve this goal we operate the system in burst mode, where one burst is amplified within a single pump cycle. This operation regime enables us to operate the laser close to its saturation fluence. Together with the depopulation of the lower laser levels at cryogenic temperatures, high extraction efficiencies are possible even for the long lifetime, low gain laser material.

The long fluorescence life time allows to reduce the power requirement of the pump source and therefore increase the cost-effectiveness of the laser.

An additional consequence of the higher efficiency in the burst mode is a lower thermal load of the amplifier material. On the other hand achievable intensities are much higher than using long pulses. That is why such a system is ideal for all applications where high peak and moderate average power are needed. Especially for reduced heat affected material processing or for scientific applications in combination with particle accelerators, which operate in similar pulse modes this kind of laser will be advantageous.

The presented laser system is designed to deliver 5J per burst at a repetition rate of 10Hz. The burst duration is adjustable within 0.1 and 1ms while a single pulse width is 200fs. The repetition rate within the burst is up to 1MHz. Pulses seeding the three stage system are stretched to 200ps for chirped pulse amplification. The first amplifier is operated continuously pumped at room temperature whereas the following two stages are pulsed and cryogenically cooled.

8780-8, Session 2

Multikilowatt cryogenic Faraday isolator with the disk-shaped composite magnetooptical element

Dmitry S. Zheleznov, Alexey V. Starobor, Ivan B. Mukhin, Oleg V. Palashov, Institute of Applied Physics (Russian Federation)

At present, manufacturing of the composite optical elements becomes very popular technology which is increasingly used in the areas of optics, associated with high output laser power. Now various composite element are widely used: the Fabry-Perot elements, Nd:YAG / Cr:YAG in microchip lasers, Yb:YAG with Cr:YAG cladding, etc. Such configuration of the optical element allows either suppressing the parasitic amplification or significantly improving the heatsink from the primary optical element to reduce the introduced thermal distortions of the radiation. Our work is dedicated to the manufacturing the composite magnetooptical elements (MOE) for the Faraday isolators (FIs).

The point is that the intense development of laser sources average power enhancement demands reduction of thermal effects appearing in different optical elements due to laser radiation absorption. The Faraday isolators are the devices subject to significant thermal self-action because of strong absorption (~10-3cm-1) of its MOE. Therefore, the main important FIs characteristic - the isolation ratio - is determined by thermally induced depolarization. There are different ways to decrease the thermally induced depolarization in FI. For example, cooling FI to cryogenic temperatures (T <100K). The magneto-optical figure-of-merit M (it characterizes the medium impact on the FI isolation degree at high average power), increases by cooling, which leads to a reduction of thermal effects. Use of traditional media terbium-gallium garnet (TGG) for cryogenic FI (CFI) cause to significant shortening of the MOE and transition to the disk geometry with the heatsink through the optical surface, thus providing substantial reduction of the transverse temperature gradient and additional suppression of thermally induced depolarization.

In our experiments we investigated CFI with disk-shaped MOE of terbium-gallium garnet crystal (TGG) with [001] orientation, length 3.4 mm, diameter of 10.3 mm and absorption coefficient 7•10-4 cm-1. It was demonstrated stable isolation at powers up to 1400W. The isolation ratio of the CFI with TGG was more than 30 dBs. After that the disk-shaped MOE of TGG was pressed against a sapphire disk 1.6 mm thick, thus providing thermal contact with it. The main advantage of sapphire is a thermal conductivity increasing on cooling down to 250 W/m?K. The isolation ratio was increased up to 33 dB at the 1400 W. Then we have investigated a composite MOE consisting of a TGG-disk and a 1-mm-long YAG-disk. Despite a lower thermal conductivity (88 W/m?K at 80 K) as compared to sapphire, YAG can effectively remove heat from TGG. In the composite MOE with YAG-disk, isolation ratio increases to 38 dB at 705 W. These results are consistent with the results of numerical calculations, which show additionally that if a TGG crystal is cooled from both ends by two YAG crystals the maximum laser power needed to ensure the isolation ratio of 25 dB is 6 kW. Moreover, using of the original technique of thermodiffusion welding in producing the composite MOE will greatly increase the sturdiness of the contact.

8780-9, Session 3

High-power, picosecond pulse thin-disk lasers in the Hilase project

Michal Chyla, Taisuke Miura, Martin Smrz, Akira Endo, Tomas Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

High-energy laser source generating ps-pulses is an attractive solution for EUV plasma sources commonly used in science and industry. Within Hilase Project we are conducting research on both 500 mJ, 1 kHz and 5 mJ, 100 kHz picosecond laser sources based on the Yb:YAG thin-disk technology.

Achieving this high-energy entails overcoming major challenges associated with required large mode diameter on the thin-disk and high-intensity pumping. Due to large mode size, any deformations of the thin-disk cause optical phase distortions and influence proper mode matching. Since we use high- intensity pump laser diodes, deformations of the thin-disk are inevitable due to high thermal load and induced stresses. As a solution, we offer thin-disk deformation correction method and zero-phonon-line pumping to decrease the thermal load. We measure the thin-disk deformations by utilizing a Shack-Hartmann wavefront sensor. Basing on the results, cavity is optimized in respect to the corrected thin-disk curvature. Zero-phonon-line pumping at 969 nm has the advantage of smaller quantum defect and therefore less heat is generated in the gain media, thereby overall efficiency is improved. Nevertheless, 969 nm linewidth is much narrower (<1.5 nm) than standard 940 nm linewidth (6 nm) and requires using of volume Bragg gratings for wavelength stabilization.

In order to evaluate the advantage of zero-phonon-line pumping, we first developed a regenerative amplifier with a standard pumping laser diode at 940 nm for comparison. The mode size on the thin-disk of 2 mm and cavity length of 4.5 m assured stable operation in CW at low pump power. The thin-disk curvature in the regenerative amplifier changed together with increasing pump power, and at 200 W of pump power, the thin-disk curvature especially in sagittal direction changed about 1 m. After computer-aided cavity optimization, stable operation at higher pump power was achieved. In order to evaluate feasibility of high-energy regenerative amplifier we developed a water-cooled Pockels cell operating up to 10 kHz repetition rate with the quarter wave voltage of 10.5 kV. Further increase in repetition rate up to 1 MHz is planned. At present we obtained output power of 20 W at 10 kHz repetition rate pumping at 940 nm. The amplified beam with 4 mm diameter is focusable to 40 μm, which implies M2 parameter in range of 1.2-1.5. Evaluation of different pumping wavelengths requires additional experimental work. Obtained comparison results and further discussion will be presented.

8780-10, Session 3

10GW diode-pumped femtosecond laser operation from 1036nm to 1053nm based on Yb:CaF2

Antoine Courjaud, Vincent Clet, Amplitude Systèmes (France); Patrice Camy, Jean-Louis Doualan, Richard Moncorgé, Ecole Nationale Supérieure d'Ingenieurs de Caen et Ctr. de Recherche (France); Eric P. Mottay, Amplitude Systèmes (France)

Among all the numerous applications of ultrafast lasers, some require high peak power, for secondary sources such as THz, Xray generation, or analysis such as LIBS or ICPM [1,2]. Other interest appears in or photoelectron emission using deep-UV photons [3]. Those applications require compact and stable systems, at high repetition rate. Diode-pumped technology is a solution of choice to address those requirements,

Recently, we demonstrated the broad tunability of Yb:CaF2 at room temperature from 1030 to 1065nm in Q-switched regime, with an optimal pulse energy around 1050nm [4]. We report here on an ultrafast laser based on an Yb:CaF2 regenerative amplifier operating in the multi-millijoule regime at a repetition rate around 100Hz.

The system consists in a femtosecond oscillator, a grating based stretcher, a regenerative amplifier based on a Yb:CaF2 crystal pumped by a CW 20W fiber-coupled laserdiode, and a grating based compressor. Two different femtosecond oscillators can be used to seed the regenerative amplifier : the first one delivering ultrashort pulses at a central wavelength of 1036nm, and a second centered at 1053nm.

The regenerative amplifier delivers 5mJ pulses at 100Hz repetition rate, and 4mJ at 300Hz, at a central wavelength of 1038nm when injected with 1036nm oscillator, and 1048nm when injected with 1053nm oscillator. The amplified pulses are subsequently compressed to a pulse duration of 320fs, with a pulse energy of 3,2mJ at 100Hz and 2,7mJ at 300Hz, corresponding to a peak power exceeding 10GW. The amplifier can be tuned to 1053nm central wavelength, emitting 2mJ pulses with 600fs pulse duration. The beam quality is excellent, and the pulse-to-pulse stability is 0,3% rms.

Frequency conversion to 260nm leads to 300µJ pulse energy with a pulse-pulse stability below 1% rms, and an excellent Gaussian beam quality.

8780-11, Session 3

Post compression of multi mJ Terawatt femtosecond pulses and generation of attosecond pulses at high energy

Ondrej Hort, Antoine Dubrouil, Coralie Fourcade-Dutin, Stéphane Petit, Eric Mével, Dominique Descamps, Eric Constant, Univ. Bordeaux 1 (France)

High energy isolated attosecond (1 as = 1E-18 s) pulses can be generated using high energy few cycle-laser pulses via high-harmonic-generation in gases [1] or on plasmas [2]. Such high energy attosecond pulses are a key to perform nonlinear processes with XUV photons. To generate them, high energy ultra-short laser pulses with a high quality beam profile are needed. It is still not common to fulfill both conditions.

One possible approach is the guided post compression with hollow core capillary filled with noble gas [3, 4]. Kerr induced self-phase-modulation effect is often used to broaden the pulse spectra with this approach. The pulse energy is however limited as high gas pressure are needed and the corresponding beam critical power is low. Similar energy limitations exist with filament based post compression [5].

We have developed an alternative post compression approach using optical-field-ionization induced spectral broadening at low gas pressure in a guided geometry [6] to overcome this energy limit. Our technique is well adapted for high energy pulse post compression and allowed us for the first time to our knowledge to post compress pulses with energy higher than 10 mJ. We obtained pulses with duration of 8 fs FWHM and 8.7 mJ of energy or 10 fs pulses with 11 mJ energy preserving the TW peak power.

These high energy few cycle pulses were used to generate high harmonics. The XUV pulses had enough energy to be studied with both spatial and spectral resolution on a single shot basis. These high resolution single shot spectra showed continuous spectra with strong spatial and spectral structures that were not previously reported.

8780-12, Session 3

Key elements of alignment of the chirped pulse compressor

Ivan V. Yakovlev, Institute of Applied Physics (Russian Federation)

In recent years, great attention has been given to the development of petawatt and multipetawatt laser systems based on the technique of chirped pulse amplification (CPA) and optical parametric chirped pulse amplification (OPCPA). Some principal elements of CPA systems are diffraction grating-based stretchers and compressors. Despite wide experience in development of compressors, there is no standard algorithm for controlling and adjustment of these devices.

The quality of a recompressed pulse at the CPA system output depends on the accuracy of a stretcher and a compressor matching. For petawatt systems with the laser beams several tens of centimeters in diameter, the accuracy required for adjustment of angular positions of compressor gratings reaches unities or even fractions of angular seconds.

The report considers the methods for adjustment of grating compressors of chirped pulses for high-power femtosecond CPA laser systems. Special attention is paid to a design of the compressor elements that play a crucial role in exact adjustment of diffraction gratings over three rotational degrees of freedom. Adjustment of the grating block lies in positioning of the grating working surface and grooves directing parallel to the vertical rotation axis with the second accuracy. The procedure is carried out by means of an autocollimator and a glass adjusting cube with pairwise parallel polished opposite sides. Digital processing of the autocollimation grid image can easily provide subsecond accuracy of measurements.

The optical system for the compressor adjustment allowed setting the input beam normally to the grating rotation vertical axis and, correspondingly, to grooves. It was accomplished using continuous radiation of a He-Ne laser and that of a diode laser with the wavelength of 0.91 um. Grating rotation angles, the angle of the radiation incidence onto the first compressor grating included, were determined based on the known grating grooves densities and the wavelengths of adjusting radiations.

Such output radiation parameters as the minimal pulse duration, homogeneity of duration over the cross-section of the beam, and the absence of angular dispersion served as a final criterion of the performed compressor adjustment. Residual angular dispersion in the vertical and horizontal planes was controlled.

It is known that different densities of grooves in the diffraction gratings used in compressors cause non-compensated angular dispersion. The report offers an easy-to-implement method which allows measuring the difference of grating groove densities with the accuracy better than 0.005 lines/mm. The accuracy of measurements can be improved by more than one order using grazing reflection angles and digital processing.

The original methods presented in the report were successfully used for alignment of grating compressors in the petawatt PEARL and FEMTA laser complexes. Application of the proposed methods for adjustment of compressors of high-power CPA and OPCPA laser systems with tiled gratings seems to be particularly useful and challenging.

8780-13, Session 4

Thermo-optical measurements of ytterbium doped ceramics (Sc2O3, Y2O3, Lu2O3, YAG) and crystals (YAG, CaF2) at cryogenic temperatures *(Invited Paper)*

Bruno Le Garrec, Academy of Sciences of the Czech Republic (Czech Republic); Vanessa Cardinali, Commissariat à l'Énergie Atomique (France); Gilbert L. Bourdet, Ecole Polytechnique (France)

Heat generation in solid-state media represents the main limiting feature for power scaling diode-pumped solid-state lasers (DPSSL). Heat induces thermal distortions of the beam wavefront and perturbs the quality of the focused spot, preventing from the use of high repetition rates. Nevertheless, one can carefully choose the gain medium and use this medium at cryogenic temperature. Yb doped ceramic lasers are very promising solutions for high average power solid state lasers but their thermo-optical properties are unknown especially at cryogenic temperature. Thermal conductivity depends on the temperature and on other intrinsic parameters of the material such as the doping level or the grain size. There is a simple model that shows that the thermal conductivity of ytterbium doped Y2O3 and Sc2O3 decreases when the doping level increases, while ytterbium doped Lu2O3 remains constant. Last year, we reported measurements of the thermal expansion coefficients and the thermo-optic coefficients dn/dT of Ytterbium doped cubic sesquioxides (Sc2O3, Y2O3, Lu2O3) ceramics and of Ytterbium doped crystals (YAG, CaF2) that we made at room and cryogenic temperatures. We have decided to develop our own method of measurement: first, we have made measurements at room temperature with different known materials like YAG, and second we have made measurements at low temperature in our cryostat. We have tested Y2O3 and YAG both undoped and ytterbium doped ceramics, 1 at. % Yb doped Lu2O3 and Sc2O3 ceramics, Yb:YAG crystals with different doping levels and CaF2 both undoped and ytterbium doped crystals.

8780-14, Session 4

Optical and laser damage properties of Yb3+:CaF2 for laser applications

Gordon von der Goenna, Thomas Töpfer, Karin Poehl, Andreas Weisleder, Hellma Materials GmbH (Germany); Joachim Hein, Jörg Körner, Friedrich-Schiller-Univ. Jena (Germany)

Yb3+ doped CaF2 is a favorable material for high peak power Diode Pumped Solid State lasers. With the authors´ process crystals of a diameter up to 350mm and a thickness up to 200mm are grown. This makes Yb3+:CaF2 available for large aperture applications.

Data of refractive index homogeneity and stress birefringence for large aperture optics are presented. The refractive index change over temperature change (dn/dT) depending on the dopant concentration is shown.

Absorption and emission cross section at different temperatures are reported.

The laser damage behavior of polished and coated laser crystals is presented.

8780-15, Session 4

Spectroscopic characterization of various Yb3+ doped laser materials at cryogenic temperatures for the development of high energy class diode pumped solid state lasers

Venkatesan Jambunathan, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Jörg Körner, Friedrich-Schiller-Univ. Jena (Germany); Pawel Sikociniski, Martin Divoky, Magdalena Sawicka, Antonio Lucianetti, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Joachim Hein, Friedrich-Schiller-Univ. Jena (Germany); Tomas Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

In recent years, there has been a considerable interest in Yb3+ (Yb) doped laser materials because of very low quantum defect and absence of exited state absorption. Easy availability of diode lasers as pump sources that match the absorption bands of Yb-doped laser materials has stimulated the development of high energy class lasers of the order of 100 J to KJ level which has potential applications in the field of science and technology. Several research groups including Polaris, Penelope, LUCIA, Dipole have developed and some proposed projects (ELI, HiPER, and HiLASE) are in the process of developing lasers of this class and are focused on design and modelling of various Yb-doped materials. Many such systems will achieve output laser parameters by cooling the gain media at cryogenic temperatures. For this reason, precise and reliable spectroscopic data such as absorption and emission cross-sections are necessary because these factors will help in the determination of crucial design parameters such as small signal gain, exact pump wavelength, absorption band width etc.,

Bearing in mind these needs, this work is focused on the spectroscopic characterisation of various Yb doped gain media namely Yb:YAG, Yb:LuAG, Yb:FP15-glass and Yb:CaF2 at cryogenic temperatures in the 80 – 340 K range.

The measurement setup will be described. In addition, we will describe how the data for absorption cross-section using Beer Lamberts law and emission cross-section using two methods such as reciprocity method and Fuchtbauer-Landenburg method were processed. Finally, the spectroscopic results and their impact on laser performance at cryogenic temperatures will be discussed in detail.

8780-16, Session 4

Laser-induced damage down to few cycle pulse duration: test bench and measurements

Marc L. Sentis, Lasers, Plasmas et Procédés Photoniques (France); Olivier P. Uteza, Nicolas Sanner, Raphael G. C. R. Clady, Aix-Marseille Univ. (France)

The metrology of laser induced damage is essential for the development of high average power and high intensity laser sources, and reliable use of optical components in general. In this paper, we present results of laser induced damage threshold (LIDT) of fused silica, sapphire and Ti:Sa crystals in single shot mode and for laser pulse duration from nanosecond down to few cycle (< 10 fs) pulsed regime.

The experimental setup includes i) a module to focus the laser using either refractive or reflective optics; ii) a module to control the laser irradiation parameters; iii) a module to manage the target; and iv) a module to characterize in-situ the damage using optical microscopy or diffuse light scattering. Ex-situ analysis based on optical microscopy, AFM and SEM is also performed, allowing accurate measurements of damage and ablation thresholds of optical materials and components. Using a single experiment, our methodology then yields accurate determination of damage/ablation threshold of any material (or component) irradiated by pulsed laser [1], as well as complementary physical results characterizing laser–matter interaction and/or concerning the deterministic character of femtosecond damage [2,3].

For fused silica, we model and measure the damage and ablation threshold as well as the deterministic character of femtosecond laser-induced damage for pulses ranging from 7 fs to 300 fs (academic collaboration with INRS and Celia). The agreement between the numerical and experimental results on a wide range of pulse duration (< 10 fs – 300 fs) asserts that impact ionization plays a role whatever the interaction regime and that its relative importance in the process of material ionization gradually increases with the pulse duration. It is also shown that the abrupt decrease of both damage and ablation thresholds observed with short pulses (< 30 fs) is related to the significance of tunnel ionization in the ultrashort regime. Moreover, the results indicate that the laser damage occurrence is more deterministic below 30 fs [2-4].

In the frame of an academic and industrial collaboration (Amplitude technologies, I. Fresnel, LOA and LP3), bulk laser-induced damage threshold fluence of Ti:Sapphire is determined under single pulse irradiation from femtosecond to nanosecond temporal regimes in the visible and near-infrared spectral domains. In the range of explored laser conditions, the laser-induced damage threshold fluence increases with both pulse duration and wavelength. The results are also compared to laser interaction with Sapphire samples. We demonstrated that Ti^{3+} doping of Sapphire does not weaken the laser-induced damage resistance of Sapphire lattice. An explanation can be the addition of supplementary energy dissipation channels by radiative and fast non-radiative relaxation processes [5].

Finally a new LIDT test bench using the very recent ASUR facility will be introduced. Thanks to the unique laser characteristics of ASUR facility (25 fs - 10 TW – 100 Hz), LIDT tests can be performed under a large set of experimental laser conditions unmatched by other set-ups: small and large beams, laser pulse duration between < 10 fs and 500 fs at 800 nm, wide spectral band (240 nm to 9 µm) using an OPA system, and operation under vacuum or ambient air.

References

[1] N. Sanner et al., Appl. Phys. A 94 (4), pp. 889-897 (2009).

[2] N. Sanner et al. Appl. Phys. Lett. 96, pp. 071111-3 (2010).

[3] B. Chimier et al., Phys. Rev. B. 84, pp. 094104-10 (2011).

[4] O. Utéza et al., Appl. Phys. A 105, pp. 131-141 (2011).

[5] B. Bussière et al., Applied Optics, accepted for publication 2012.

8780-17, Session 5

Multipass amplifiers of Polaris

Sebastian Keppler, Joachim Hein, Friedrich-Schiller-Univ. Jena (Germany); Marco Hornung, Ragnar Bödefeld, Alexander Kessler, Helmholtz Institut Jena (Germany); Christoph Wandt, Max-Planck-Institut für Quantenoptik (Germany); Alexander Sävert, Marco Hellwing, Friedrich-Schiller-Univ. Jena (Germany); Franke Schorcht, Helmholtz Institut Jena (Germany); Malte C. Kaluza, Friedrich-Schiller-Univ. Jena (Germany)

In order to increase the important laser parameters of the POLARIS laser system, which is operated at the University of Jena, in particular energy, bandwidth and focusability, new amplifier technologies have been developed together with a further improvement of the existing elements of the laser system. In this talk we give an overview about the current status of the main amplifiers of POLARIS including recent results as well as an outlook for the near future.

For an optimized near-field profile as well as a smooth wavefront, amplifiers based on relay imaging are a very promising alternative to conventional multipass amplifiers. Based on this principle, we have developed a new amplification stage, which will replace two of the currently used ones. New homogenized pump modules and the imaging principle ensure an optimal top-hat shaped output profile. Furthermore, this amplifier provides newly developed technologies regarding the amplified beam profile, the spatial filtering and the divergence control. Currently this amplifier provides a total gain of 100 with an improved energy stability of <3.5% (RMS) in a daily operation mode. Eventually, the amplifier will operate under vacuum conditions and will provide an output energy of up to 1.5J per pulse.

Furthermore we investigated an advanced method for the homogenization of the multi-spot composed pump profile of the amplifier A4, which improved the homogeneity to <±2% (peak to valley). The homogeneity is a crucial parameter for the near-field profile, which affects the focusability and the maximum output energy regarding the fluence. The new method comprises a computer-based evolutionary algorithm which optimizes the position of the different spots regarding its individual size, shape and intensity. These preliminary investigations are indispensable for the final amplification stage A5.

8780-18, Session 5

Characterization of Yb:YAG active slab media based on a layered structure with different doping levels

Antonio Lapucci, Marco Ciofini, Istituto Nazionale di Ottica (Italy); Laura Esposito, Leonida A. Gizzi, Jan Hostasa, Luca Labate, Angela Pirri, Guido Toci, Matteo Vannini, Consiglio Nazionale delle Ricerche (Italy)

Ytterbium doped YAG materials are the chief candidates for the attainment of High Energy Diode Pumped Solid State Laser (DPSSL) systems working in high rep. rate pulsed regimes. YAG ceramics have already proven their advantages over single crystals for high average power systems, both in terms of higher fracture limit levels and in terms of ease of production. Recently structured slabs have been obtained in YAG ceramics shaped from a stack of layers with different doping levels. In the CNR-ISTEC laboratories the formation process is based on the preparation of the single layer from powders by linear pressing and the subsequent stacking of the different layers followed by a cold isostatic pressing. Calcination, reaction sintering annealing and polishing processes complete the slab production. In this paper we present the thermo-mechanical modeling based on Finite Element Mesh (FEM) methods and the first experimental results obtained with some simple structured samples. Numerical simulations are presented for single- or double-sided pumping and different cooling geometries. They show that structured slabs can reduce thermal gradients respect to the uniformly doped means with comparable absorption and geometry. This will mean a reduction of thermal lens effect and thus an increase of maximum allowed pump power loading. Previous literature reports some work made with structured slabs where higher doping was located in layers where pump radiation resulted lower, in order to get a more uniform absorption. Interestingly our modeling indicates that reduced gradients are more effectively obtained when a higher doping is located close to the cooled surfaces. The first experimental results confirm the indications of our numerical simulations.

8780-19, Session 5

LD-pumped erbium and neodymium lasers with high energy and output beam quality

Gennady I. Ryabtsev, Vladimir V. Kabanov, Tatiana V. Bezyazychnaya, Alexandr V. Grigor'ev, Maxim V. Bogdanovich, Yahor V. Lebiadok, Kirill V. Lepchenkov, B.I. Stepanov Institute of Physics (Belarus); Andrew V. Ryabtsev, Maxim A. Shchemelev, Belarusian State Univ. (Belarus)

Laser diode pumped erbium glass and Nd:YAG lasers physical and fabrication peculiarities which provide the high output energy and beam quality are considered. Developed design approach allow to make passively Q-switched erbium glass eye-safe portable laser sources with output energy 8 - 12mJ (output pulse duration is less than 25 ns, pulse repetition rate up to 5 Hz) and beam quality M2 less than 1.3. To reach these values the erbium laser pump unit parameters were optimized also. Namely, for laser diode arrays optimal near-field fill-factor, output mirror reflectivity and heterostructure properties were determined. Construction of the lasers as well as the optical properties of the active element and pump unit makes possible the laser operation within wide temperature interval.

The transversally pumped Nd:YAG laser output beam uniformity was investigated depending on the active element (AE) pump conditions. In particular, to provide pump uniformity within AE, a special layer, which doesn't absorb the pump radiation but effectively scatters the pump and lasing beams, was used. Application of such layer results in amplified spontaneous emission suppression and an improvement of laser output beam uniformity. The carried out investigations allow to fabricate solid-state Nd:YAG lasers (1064 nm) with the output energy 250 mJ for pulse repetition rate 30 Hz and output energy 50 mJ for pulse repetition rate 100 Hz. Also the laser sources with following characteristics: 35 mJ, 30 Hz (266 nm); 60 mJ, 30 Hz (355 nm); 100 mJ, 30 Hz (532 nm) were manufactured on the base of developed Nd:YAG quantrons.

8780-20, Session 5

10J/1Hz Water-cooled Yb:YAG laser system

Jian-gang Zheng, Jun Zhang, Zhen-guo Wang, Xiong-wei Yan, Xin-ying Jiang, Deng-sheng Wu, Xiao-ling Tian, Xiong-jun Zhang, Ming-zhong Li, Qi-hua Zhu, China Academy of Engineering Physics (China)

The Yb:YAG crystal has attracted the wide researcher's interesting in high-average-power laser because of the its outstanding performance, including long lifetime of the upper energy level, high thermal conductivity, the absent from quenching in the case of high Yb concentration and suitable for LD pumping, especially the emergence of Yb:YAG Ceramics in recent years pull the research to a high level. In this article, we report the Yb:YAG based 10J repetition rate ns laser system and its key techniques.

The system includes three parts: laser source, multi-pass preamplifier and two stage main amplifiers. In this system, the Yb:YAG crystal or ceramic was selected as the gain material, and it was cooled by mean of water laminar flow in the amplifier's laser-head, the laser is multi-pass V-shape amplified in the laser head to get higher gain. The laser source output about 10mJ energy with gauss shape. And it is amplified to about 100mJ in the multi-pass V-shape preamplifier, and then the laser was expanded and shaped from gauss to a 9mmX9mm square with 10mJ energy. In the main amplifier, the square shaped laser was firstly multi-pass V-shape amplified to about 1J, and then it was delivered to the second amplifier. The second amplifier consisted of two laser-head, one was pumped by 60kW LD-array, and the other by 80kW, the peak pumping power to the gain material was about 20kW/cm2, the laser was four pass amplified in the two-laser-head amplifier. The concentration of the Yb was 5at.%. the small signal gain in the two amplifier was about 2 times for a single V-shape pass, and the pumping duration is about 800?s. During the primary integration of system the system output maximum energy about 7.5J/1Hz/10ns.

In the primary test of system, the total output energy was lower than expectation. The reason is that, the density of the doped Yb ion in the gain materials is too high, resulting in the higher energy storage, serious ASE in amplifiers, and it has to shorten the pumping duration to decrease the unnecessary thermal deposition in gain materials.

To increase the total energy storages, the gain material has been designed again. The gain material changed from Yb:YAG crystal to ceramic, the concentration of the doped Yb ion decreased from 5at.% to 3at.%, and the Yb:YAG ceramic surrounded by Cr:YAG ceramic to absorb the ASE. We have measured the small signal gain of amplifier based-on the new materials, it showed that, the small signal gain for a single V-shape pass amplification increased from original 2 times to 3times, in the primary integration experiment 8.5J/1Hz/10ns output energy was got, it indicate that, the new system based-on the new material can provide above 10J output energy.

8780-21, Session 6

Deformable mirror technologies at adaptive optics/xinetics

Allan Wirth, Kevin M. Ezzo, Jeffrey L. Cavaco, Northrop Grumman Xinetics (United States)

AOA Xinetics has been at the forefront of Deformable Mirror (DM) technology development for over two decades. In this paper the current state of that technology is reviewed and the particular strengths and weaknesses of the various DM architectures are presented. Emphasis is placed on the requirements for DMs applied to the correction of high-energy and high average power lasers. Mirror designs optimized for the correction of typical thermal lensing effects in diode pumped solid-state lasers will be detailed and their capabilities summarized. Passive thermal management techniques that allow long laser run times to be supported will also be discussed.

8780-22, Session 6

Optimized cooling base for end-pumped solid-state laser rods

Stavros Boukios, ThyssenKrupp AG (Germany); Christos Evagelatos, Univ. of Athens (Greece); Giorgos Avdikos, Raymetrics S.A. (Greece); Alexandros D. Papayannis, National Technical Univ. of Athens (Greece); Dimitris Papadopoulos, Univ. of Ioannina (Greece); Georgio D. Tzeremes, European Space Agency (Netherlands)

The growing need for optimal cooling systems for solid-state laser systems suitable for aerospace applications, is not covered sufficiently by the existing literature. For this reason, a novel design concept of such a system, capable of cooling and mounting end-pumped laser rods with short undoped end-cups using direct contact of the crystal with cooling water, has been developed for current research on aerospace LIDAR systems in the frame of a research project funded by the European Space Agency. Having as main objectives the minimization of the size and the weight of the laser rod cooling-mounting base and the maximization of its cooling capacity, axial flow of cooling water was chosen in order to minimize flow-induced vibrations and thus maximizing the flow speeds and consequently the heat dissipation rate, as well as providing axis-symmetrical thermal and stress conditions to the rod. The cross section of the water flow cavity is adapted to meet the heat production profile of the laser rod each time, depending on the dopant's concentration levels along the crystal. The inlet of the cooling water in the main cooling cavity is radial close to the end-cup at the pumping side of the crystal. This was achieved using a pre-chamber for the initial flow configuration and radial flow channels to the main flow cavity. A modular mechanical design was finally developed for fast and low-cost system modification resulting in considerable material and manufacturing cost reductions. Beyond conceptual optimization, structural, thermal and fluid-structure interaction simulations were conducted for numerically optimized designs using commercial FEM, CFD and optimization codes to check the system's scalability for medium and high lasing powers up to 1kW. Experimental results from Nd:YAG end-pumped laser rods with various doping levels and longitudinal distributions using 100W of diode-pumping power have been conducted and compared to the numerical simulation results to validate the reliability of the developed cooling system concept. However future experiments with laser rods pumped at higher power levels are planned to define the full capacity of the proposed cooling scheme.

8780-23, Session 6

Design of a tunable parametric wavelength conversion system between 2 and 3 um pumped by a high-average-power Yb:YAG thin-disk laser

Ondrej Novák, Taisuke Miura, Patricie Severová, Akira Endo, Tomas Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Tunable parametric sources have proved their utility in spectroscopy and other fields of applications. With increasing energy densities of laser pulses the laser induced damage threshold (LIDT) testing becomes an important characterization of optical components. The emission wavelength of several laser materials, used e.g. in medical applications, is in the 2 – 3 µm wavelength-range. We propose a wavelength conversion system generating tunable sub-ns pulses for LIDT measurements in this IR spectral range.

The pump beam of the conversion system will exploit the latest development in the field of the thin-disk laser technology, which enables to generate hundreds of mJ pulse energy at 1 kHz repetition rate with high efficiency. The Yb-fiber-laser seeded CPA system with high-energy Yb:YAG thin-tisk regenerative amplifier will produce uncompressed pulses of 0.5 ns width, 130 mJ energy, at wavelength of 1030 nm with 1 kHz repetition rate giving 130 W of average power.

Output of the thin-disk regenerative amplifier will pump an optical parametric generator (OPG) and subsequent optical parametric amplifiers (OPA). The tunable output wavelength of the OPG will be

between 1.5 µm - 2.1 µm for the signal beam and between 2.1 µm - 3 µm for the idler beam. The signal will be amplified in the OPAs because the optics and diagnostics is more easily available below 2 µm wavelength. The tunable multi-millijoule source above 2.1 µm will be the idler beam taken from the last amplification stage. High-average output power of 10 W at 1 kHz repetition rate will be unique among 2 – 3 µm tunable systems.

Operation of the amplifiers at high-intensities and high-average powers limits the system performance. The thermal load of crystals caused by the partial beam absorption will be studied. Further, the damage threshold of optical components, transmission range of nonlinear crystals, and amplifiers bandwidths will be addressed.

8780-24, Session 6

The latest developments in switch technology for high energy and RF-operation laser amplifiers in RCLF

Jun Zhang, Jian-gang Zheng, Xiong-jun Zhang, Deng-sheng Wu, Xiao-ling Tian, Kuixing Zheng, China Academy of Engineering Physics (China)

Studies of the design of high energy rf-operation laser amplifiers show that a multipass amplifier architecture offers a significant cost saving and extraction efficiency increasing. An optical switch is very important to control numbers of amplifying passes and to suppress self-excitation oscillation in a multi-pass amplifier, especially in a high stored energy and high saturation fluence gain media amplifier. Unfortunately, the existing switch technologies can't meet the needs of clear aperture and thermal properties at the same time in the case of high energy and rf operation. We manufacture a 10Hz, single-pulse driven, ?30mmx3mm DKDP crystal plasma-electrodes Pockels cell (PEPC). This device, with 4000:1 extinction ratio (ER), 99.8% switching efficiency (SE), and 8.6ns rise time, can be used for injection locking in a regenerative amplifier within 260mW/cm2 laser average power density without drawback of switch performance. Furthermore, we propose and demonstrate a conduction-cooled 10Hz PEPC, which is developed for multi-tens W/cm2 average power density amplifier application. The device, constructed with two plasma chambers providing double-sides electrodes, and longitudinally driven by two ±15kV voltages pulse generators, adopts a piece of 70mmx70mmx7mm white stone to cool two pieces of 50mmx50mmx5mm DKDP crystal. The measured results indicate: the transmission ratio 97.2%, the wave-front distortion PV value 0.3?(?=632.8nm), the ER 2347:1, the SE 99.7%, and the rise time 12ns. With regard to "hot" properties, the simulation results show: if the PEPC was exposed to 50W/cm2 (5J/cm2@10Hz) laser irradiation, the contact thermal resistance between the DKDP and the white stone should be no more than 20cm2K/W to avoid thermal facture on the DKDP surface and to promising the ER greater than 1000:1. To estimate optimistically, the developed conduction-joint technique meets this requirement. We are now preparing a heating source for the later thermal effects studying.

8780-25, Session 7

Preliminary experimental and simulation results of the ESA QOMA project: a new DPSS laser source suitable for space applications

George Tsaknakis, National Technical Univ. of Athens (Greece); Dimitris N. Papadopoulos, Ecole Nationale Supérieure de Techniques Avancées (France); Christos Evagelatos, Paraskevas Bakopoulos, Univ. of Athens (Greece); Georgios K. Avdikos, National Technical Univ. of Athens (Greece); Loïc Deyra, Univ. Paris-Sud 11 (France); François Balembois, Patrick Georges, Lab. Charles Fabry (France); Alexandros D. Papayannis, National Technical Univ. of Athens (Greece); Stavros Boukios, ThyssenKrupp AG (Germany); Georgios D. Tzeremes, European Space Agency (Netherlands)

In the paper, we present preliminary results obtained in the frame of the QOMA project (Q-Switched Master Oscillator based on Multidoping Nd:YAG Technology for Optoelectronics Space Applications) funded by the European Space Agency (ESA). This project is a collaboration between ESA, Raymetrics S.A., and the National Technical University of Athens (NTUA). The main goal of the project is the design, development and manufacture of a new low-weight, high-power diode-pumped laser source for application in future space-borne optoelectronic and lidar systems, dedicated to the study and monitoring of aerosols and the space environment. The system's design is based on new laser engineering technologies combining high power pumping of a multi-segmented crystal rods at 885nm and novel crystal cooling configurations. As active material a multi-segmented Nd:YAG crystal rod (0.1%, 0.23%, 0.6% at Nd) of 54 mm length and 3 mm diameter with 7 mm undoped endcaps on both ends will be used. The use of the specific crystal, as an active material ensures: a high overall efficiency, in combination with excellent beam quality and high average power due to the low thermal effects and mechanical stresses inside the crystal rod. In order to optimize the system's design and performance, laser cavities with uniform rods were first simulated by the LASCAD software. Preliminary experimental results were performed with a uniformly doped 50 mm long, 1 mm diameter, 0.2% at Nd crystal (Taranis module from Fibercryst), end-pumped by a fiber-coupled diode which delivers up to 100 W at 885 nm (nLight) in collaboration with the Laboratoire Charles Fabry. Despite the relatively low doping level of this crystal, absorption reached a satisfactory high efficiency of about 65%. For 65 W absorbed pump power an output of 37 W was obtained at continuous wave operation. The M2 at this level of operation was measured at ~7 indicating a highly multimode operation. To verify the validity of our simulations the specific experimental parameters were used as inputs in the LASCAD which predicted a maximum output power of 38.7 W and an M2 value close to the measured ones. In this paper we will present our experimental results based on an optimized cavity configuration taking advantage of an innovative crystal cooling system in combination to the multi-segmented crystal technology towards a higher beam quality and an efficient laser operation.

8780-26, Session 7

Highly efficient, diode-side-pumped Nd:YLF laser emitting in fundamental mode at 1313 nm, based on the double-beam-mode-controlling (DBMC) technique

Niklaus U. Wetter, Márcio A. P. Aparicio Lopez, Instituto de Pesquisas Energéticas e Nucleares (Brazil); Alessandro M. Deana, UNINOVE (Brazil)

Highly efficient, diode-side-pumped Nd:YLF laser emitting in fundamental mode at 1313 nm, based on the double-beam-mode-controlling (DBMC) technique

Diode-side-pumping technology is the most common choice for solid state laser engineering when high power and scalability is a main issue. However, this design is generally associated with lower beam quality and efficiency. Diode-longitudinal-pumping schemes have demonstrated high beam quality and efficiency, but are rather limited with regard to power scalability because of the low thermal fracture limit of the crystals. Only a few power scalable architectures allow for high efficiency and good beam quality using the side-pumping technique, but they are usually associated with complex configurations that require specially tailored and coated gain media thereby significantly increasing cost and complexity.

In order to develop a versatile laser source capable of delivering watt-level power with high efficiency, diffraction limited beam quality, reduced costs and complexity we present a Nd:YLiF4 diode-side-pumped laser design based on a gain–guided approach that employs a double-beam mode controlling technique, in which the fundamental laser mode makes a double bounce at the crystal's pump surface. This compact folded resonator design uses a simple rectangular slab of gain media at Brewster angle that does not require coatings and therefore is cost-efficient and robust and suited for short pulse Q-switching. The design has demonstrated the highest efficiency ever reported for a diode-pumped Nd:YLF laser emitting at the main 4F3/2?4I11/2 laser transition (Wetter et al., 2009).

Lasers emitting at 1.3 micrometers have important applications in the

fields of fiber-optics, spectroscopy and health care due to diverse characteristics such as high water absorption and low dispersion in quartz. Longitudinal pumping schemes have obtained 30% of optical-to-optical efficiency at the sigma transition of 1313 nm with 3.1 W of output power (Li et al., 2011).

Using standard 1 mol% of neodymium doping, we demonstrate for the first time, to the best of our knowledge, efficient operation of the 4F3/2 ? 4I13/2 laser transition in a diode-side-pumped resonator. By pumping at 797 nm with 19.8 W TE-polarized diode bar that was focused into the crystal (spot size 5 mm x 0.1 mm) using a simple spherical lens of f=2.5cm, 7.8 W of peak output power in fundamental mode were extracted by using a three-mirror cavity comprised by a folding mirror of 8 m radius of curvature, a plane HR end mirror and a plane output coupler with 4% transmission for the emission line at 1313 nm (?-polarization). The measured optical-to-optical efficiency was 31.6% and the slope efficiency was 39.5% operating in the quasi-cw regime. The setup showed losses of 1.5% and a pumping efficiency of 76%.

LI, C. L., ZHANG, X. H., LIANG, W. & ZHAO, Z. M. 2011. Diode-pumped continuous-wave Nd:YLF laser at 1313 nm. Laser Physics, 21, 340-342.

WETTER, N. U., SOUSA, E. C., RANIERI, I. M. & BALDOCHI, S. L. 2009. Compact, diode-side-pumped Nd(3+):YLiF(4) laser at 1053 nm with 45% efficiency and diffraction-limited quality by mode controlling. Optics Letters, 34, 292-294.

8780-27, Session 7

Powerful UV generation in the picosecond pulse trains for the CLIC drive beam photo-injector option

Mikhail Martyanov, CERN (Switzerland); Marta Csatari Divall, Paul Scherrer Institut (Switzerland); Ekaterina Gacheva, Institute of Applied Physics (Russian Federation); Christoph Hessler, Valentin Fedosseev, CERN (Switzerland)

The future Compact Linear Collider (CLIC) is under development at CERN by a collaboration of many institutes worldwide. The goal is to collide electron and positron bunches with a centre-of-mass energy of up to 7 TeV. The CLIC uses a novel two-beam concept: acceleration of a low-current main beam by means of RF power produced during the deceleration of a high-current drive beam. The RF photo-injector is a contemporary electron source for linac-based accelerators which is being considered as the baseline solution for the CLIC main beam and as an option for the drive beam. To deliver high-charge picosecond electron bunches (in case of the CLIC drive beam: 8.4 nC/bunch contained within a 140 us train with 500 MHz repetition rate) the RF photo-injector requires appropriate trains of picosecond laser pulses synchronized with the driving RF pulse in the photo-injector cavity. Given that the quantum efficiency of the Cs2Te photo-cathodes is 1-3%, the laser setup must deliver about 2uJ/pulse at 262 nm or similar, which corresponds to 1 kW of mean power within train and 7 W average UV power for a train repetition rate of 50 Hz. In addition the power requirement, the bunch-to-bunch and train-to-train fluctuations in terms of energy and beam quality must not exceed 0.1% i.e. no train envelope decay or distortion.

The feasibility of such high power UV beam production by 4th harmonic generation (FGH) of the Nd:YLF laser output is being investigated at the CLIC Test Facility 3 (CTF3) at CERN. The laser system consists of a commercial passively mode-locked Nd:YLF oscillator synchronized with the 1.5 GHz RF reference signal, a preamplifier, two diode pumped Nd:YLF amplifier stages and frequency conversion stages for green and UV generation. Our studies focus on the investigation of detrimental UV induced effects in FHG crystals and the search for the optimal geometry and mode of FHG. During the fourth harmonic generation, an accumulation of partly recoverable UV two-photon induced optical defects in a BBO crystal has been observed during the 140us train, even for a relatively low peak pulse power of about 100 MW/cm2. Although the growth of these optical defects is attributed to UV two-photon absorption, the accumulated defects lead to linear absorption of green and UV co-propagating pulses. The peculiarity of this mode of operation is that each pulse itself is very weak and basically it does not induce any considerable optical defects. However, since the train consists of about 70000 pulses and the decay time of induced defects is greater than the train duration, a deterioration of the UV beam and train envelope is clearly observable. Within the scope of these studies, the pulsed 4th harmonic generation has been modelled in detail, taking into account optical defect dynamics (accumulation, relaxation, bleaching etc.). In this work the experimental results, supported by simulations, are presented.

8780-28, Session 7

Generation of 3D ellipsoidal shaped UV laser pulses for the future XFEL low-emittance photo-injector

Anatoly K. Poteomkin, Alexey V. Andrianov, Ekaterina Gacheva, Victor Zelenogorsky, Sergey Y. Mironov, Efim A. Khazanov, Institute of Applied Physics (Russian Federation); Mikhail Martyanov, CERN (Switzerland); Evgeny M. Syresin, Joint Institute for Nuclear Research (Russian Federation); Mikhail Krasilnikov, Frank Stephan, DESY (Germany)

The European X-ray Free Electron Laser (XFEL) will allow unprecedented experiments with atomic resolution on femtosecond time scales with ultra-high peak and average brilliance photon beams of high transverse spatial coherence. Its construction has already started at DESY in Hamburg. The Photo Injector test facility at DESY in Zeuthen (PITZ) develops the electron source for the XFEL. The laser driven RF gun has to fulfill very challenging specifications on electron source performance for linac based FELs, namely it should provide electron bunches with high bunch charge (~1 nC) and extremely low transverse emittance (< 1 mm mrad). Recently the attainability of such low emittance has been experimentally proven at PITZ. But the scientific achievements of the XFEL are expected to extend dramatically with the further improvement of the electron source quality. The RF photo-injector drive laser pulse shaping is a key issue to achieve such a performance. Theoretically shown and proved by beam dynamics simulations that true 3D ellipsoidal pulse shape of the UV pulses driving the photo-injector is the optimal one with respect to Gaussian or flat-top shapes in different spatial-temporal combinations. Currently the 3D-ellipsoidal pulse shape laser is under development in IAPRAS, Russia. Our studies represented in this work are mainly devoted to the following issues:

1) 3D-ellipsoidal 7ps pulse creation by means of two liquid crystal Spatial Light Modulators (SLM) in the mixed spatial-frequency domain out of 200fs pulses;

2) Aamplification of these wide-band pulses in thin-disk Yb:KGW multi-pass amplifier without dramatic distortion of the shape;

3) 2nd and 4th harmonics generation in thin LBO and BBO crystals utilizing the angular chirp technique to achieve high efficiency of conversion without shape degradation.

Home-built two-channel Er/Yb:fiber oscillator and preamplifier delivers chirped 50ps pulses at 1030nm with 1uJ/pulse at 1MHz repetition rate in each channel. The beam from the second channel after compression down to 200fs is used as a probe beam for cross-correlation diagnostics. Fiber part of the second channel is coiled to piezo-disk to produce variable and time-dependent delay for cross-correlation.

The proposed 3D-ellipsoidal pulse shaper consists of two 2D-SLM's (one for amplitude and one for phase masking) installed inside zero-order compressor. Double pass of the setup supplemented with a 90 deg image rotation between passes provides successive access to X-frequency and Y-frequency planes respectively. Since the pulse shaping technique with SLM's is available only on the fundamental wavelength it is necessary to preserve the pulse shape during the amplification and harmonic generation. This can be archived by using wide band thin disk Yb:KGW amplifiers and by introducing a certain angular chirp to the beam before the harmonics crystals.

Theoretical considerations and first experimental results are presented in this paper.

8780-29, Session PS

Stoichiometric improvement of Tio2 optical films by using time temperature gradient annealing

Alireza Bananej, Nuclear Science and Technology Research Institute (Iran, Islamic Republic of); Zohreh Parsa, Kharazmi Univ. (Iran, Islamic Republic of); Mahdieh Khatiry, Ali Sajedi, Nuclear Science and Technology Research Institute (Iran, Islamic Republic of)

Annealing process is one of the common procedure for improving the stoichiometric properties of TiO_2 optical films after deposition process. In the usual annealing process there is not any management for increasing the temperature with respect to the time evolution, so according to the others experiments it can be seen long time necessity for obtaining the best stoichiometric property which is a negative impact from the economical points of view.

But, by using managed temperature increasing with respect to the time evolution (TTGA) the processing time can be reduced obviously while the laser induced damage threshold at the first and second harmonic of Nd:YAG laser improved considerably.

8780-30, Session PS

Modeling and optimization of thin disk structure for high power sub-joule laser

Patricie Severová, Akira Endo, Tomas Mocek, Taisuke Miura, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Thin disk method is the most promising technology to realize high power millijoule to joule level pulsed laser source with high beam quality. Although the power scaling of thin disk method in multimode operation can be done simply by increasing the mode area size on thin disk to avoid optical or mechanical damage of thin disk, single mode operation at large mode area requires precise surface flatness of gain media under the highly pump condition. Generally, thin disk is deformed by thermal stress caused by high power pump light. A critical thermal management is required especially for the single mode operation with large mode area. In this report, we describe about modeling and optimization of thin disk mounting based of numerical calculation and in-situ thermal measurement.

During the amplification process, the beam profile is distorted due to changes of the aspheric OPD (optical path difference) of thin disk. When the high power pump beam impact on thin disk, the OPD is generally changed by two reasons; the thermally induced refractive index change and the mechanical deformation caused by thermal stress. Thus, the analysis of temperature distribution in the thin disk structure is the first step of thin disk improvement.

Thin disk structure consists of several layers, each of which has different thickness with inherent thermo-optical properties. An Yb-doped gain media, of which one side is AR-coated and another side is HR-coated, is bonded on a water-cooled heat sink using a bonding material. Every layer must be considered in the numerical calculation for the precise analysis. We are using a commercial FEA (finite element analysis) software to calculate the temperature distribution and the thermal stress of thin disk structure. The OPD is calculated from the FEA results using our additional calculation code. We are also calculating about the thermal effect of non-doped crystal layer that is mainly added as a suppressor of amplified spontaneous emission.

On the other hand, we measured the deformation of thin disk using precise wavefront sensor. And we are going to measure the transient thermal response of thin disk by using a fast radiation thermometer. These experimental results are compared with our numerical results to improve the reliability of numerical modeling. Comparison of numerical results with experimental results, and improvement of thin disk structure based on the numerical calculation will be discussed at the presentation.

8780-31, Session PS

Investigation of Yb:LuAG crystals with high dopant concentration

Jan Sulc, Zbynek Hubka, Helena Jelínková, Czech Technical Univ. in Prague (Czech Republic); Karel Nejezchleb, Václav Skoda, Crytur Ltd. (Czech Republic)

Ytterbium doped LuAG ($Lu_3Al_5O_{12}$) was tested as an active medium for diode pumped laser. Similar weight and size of doping Yb^{3+} ion and substituted Lu^{3+} ion allow to obtain highly doped Yb:LuAG laser crystal without significant thermal conductivity degradation. Set of Yb:LuAG crystals with variety of doping concentrations were grown by Czochralski method. For laser experiments, two thin plates with thickness 1.05 mm and diameter 3 mm were prepared, polished, and antireflection coated (AR @ 0.9-1.1 um). The Yb-doping concentration of these samples was c=15 % and 20 %. Maximum absorption for these samples corresponds to zero-phonon line at 968.4 nm (measured absorption coefficients were 23.5 cm-1 for c=15 %and 33.9 cm-1 for c=20 %). The fluorescence decay times were 1.55 ms (c=15 %) and 1.32 ms (c=20 %). For Yb:LuAG active medium excitation, fibre coupled (fibre core diameter 100 mm, NA=0.22) laser diode with emission at wavelength 968.5 nm was used. The laser diode was operating in pulsed regime (pulse length 2 ms, repetition rate 10 Hz, maximum pulse energy 40 mJ) with low duty cycle to reduce a heat accumulation inside the active medium (Yb:LuAG crystals were not actively cooled). The longitudinally pumped Yb:LuAG samples were placed inside the 148 mm long semi-hemispherical resonator formed by a flat pumping mirror (HR @ 1.0-1.1 um, HT @ 0.97 um) and by curved output coupler (radius of curvature 150 mm). Set of output couplers with reflectivity R = 70 - 97 %@ 1.0-1.1 um was used and the output mean power was measured in dependence on pumping power amplitude. Using simultaneously measured generated pulse length the output power amplitude was calculated for estimation of CW output. It was found that for both samples the output coupler reflectivity had only minor influence on laser output parameters expect of emission wavelength (1048 nm for R > 90 % and otherwise 1031 nm). The sample with lower concentration had a lower threshold (~ 2.5 W of absorbed power amplitude for c=15 % and ~ 3.0 W for c=30 %) and higher slope efficiency (61 % in respect to absorbed power amplitude for c=15 % and 50 % for c=30 %). The maximum output power amplitude 6.7 W was obtained using Yb:LuAG with c=20 % and R=92 % for pumping power amplitude 14 W. These results confirmed the good quality of newly grown highly doped Yb:LuAG crystals.

8780-34, Session PS

Experimental and numerical of the thermal deformation of water-cooled laser mirror under high power density laser irradiation

Panpan Hu, Haihong Zhu, Huazhong Univ. of Science and Technology (China); Xiaoyan Zeng, Huazhong University of Science and Technology (China); Chongwen He, Jie Yin, Linda Ke, Huazhong Univ. of Science and Technology (China)

In this paper, experiments have been carried out to study the transient thermal deformation of laser mirror with minichannels having width of 1.3mm and interval of 2mm. Transient thermal deformation of mirror surface was simulated by coupling temperature field, obtained by solving the finite volume model of 3D laminar flow and heat transfer governing equations in FLUENT, to finite element model of thermoelastic equation in ANSYS WORKBENCH. Numerical results were validated by comparing the thermal deformation with experiment data. The highest average mean error is 9.9%. Water-cooling is an effective way of reducing thermal deformation for helping to reduce the thermal deformation of mirror surface under the absorbed heat flux as high as above 74?104W/m2 from 1.2μm to 0.86μm. It can be found that the heat conduction along the thickness direction is much faster than radial direction, which results in the large difference in temperature between radiation area and radiationless area on the mirror surface. Accroding to the highest temperature and thermal deformation appear in the downstream instead of ring-distributed

uniformly around the center of the irradiation area, the distribution of fluid flow influence the distribution of temperature to change the maximum and distribution of thermal deformation of mirror surface.

8780-35, Session PS

Characterization of diode-laser stacks for htigh-energy-class solid state lasers

Pawel Sikocinski, Martin Divoky, Antonio Lucianetti, Tomas Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Over the past 25 years, semiconductor diode-laser bars have achieved higher output powers and high power conversion efficiencies, allowing them to transition from specialty scientific items to true industrial tools. Despite continuous progress, deployment of high-power diode lasers into some applications still faces the fundamental challenge of transferring an inherently low-brightness, highly asymmetric source into an acceptable spatial arrangement. Several beam-shaping and beam-combining technologies have been developed and these advances have paved the way for a new generation of diode lasers with significantly higher brightness. Diode lasers make ideal excitation sources of solid-state lasers. Their emission spectrum can be engineered through choice of material and epitaxial structure to match any desired absorption feature in the near infrared. The narrow, engineerable emission spectrum of diodes has enabled use of solid-state laser gain materials such as ytterbium-doped yttrium aluminum garnet (Yb:YAG) that simply could not be pumped effectively with flashlamps.

Nowadays, several vendors can provide high-energy diode-laser stacks with peak powers exceeding 2 kW. In this work, we present a comparative study of high power diode stacks produced by world's leading manufacturers such as DILAS, Jenoptik, Northrop Grumman and Quantel. The diode-laser stacks are characterized by central wavelength around 939 nm, duty cycle of 1 %, and maximum repetition rate of 10 Hz. The characterization includes peak wavelength and full width at half maximum (FWHM) as a function of diode current, cooling temperature and repetition rate. Moreover, divergences of each bar of the diode stack, divergence of the whole diode stack as well as average and peak powers are measured. Mid-term stability test of spectrum and power of the diode stacks is demonstrated. The results obtained from our study show that peak wavelength of the diode stack lasers can be finely tuned to match the absorption peak of the cryogenically-cooled laser gain medium used for HiLASE project.

8780-36, Session PS

Theoretical and experimental analysis of passively Q-switched Nd:YAG rod, slab and tube laser systems

Ion I. Lancranjan, INCAS - National Institute for Aerospace Research Elie Carafoli (Romania); Roxana S. Savastru, Dan M. Savastru, Sorin I. Miclos, National Institute of Research and Development for Optoelectronics (Romania)

This paper presents the results obtained in analyzing pulsed and quasi-cw flash-lamp pumped high power Nd:YAG rod, slab and tube laser oscillators operated in passive optical Q-switching regime using LiF:F2- crystals. A numerical simulation method based on laser rate equation is developed for theoretical analysis of investigated passively Q-switched Nd:YAG laser systems. A comparison of simulation results with experimental data is also presented to certify the viability of the developed theoretical analysis method. The developed numerical simulation method is pointing to an improved design of such laser oscillators, especially by a proper choice of passive Q-switch cell initial transmission coefficient and output mirror reflectance. Laser pulses output energy of up to 500 mJ at a FWHM time duration of 5-25 ns and at a repetition frequency of 10 – 25 kHz (pps) are reported and numerical simulation of these experimental results are presented investigating the laser output parameters stability. The experimentally and theoretically investigated Nd:YAG laser systems are dedicated to material processing applications.

8780-37, Session PS

Simulation of performance of wavefront correction using deformable mirror in high-average-power laser systems

Jan Pilar, Martin Divoky, Pawel Sikocinski, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Viliam Kmetik, Ondrej Slezak, Institute of Physics of the ASCR vvi (Czech Republic); Antonio Lucianetti, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Stefano Bonora, CNR-IFN, Padova, Italy (Italy); Tomas Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

We present a code for calculation of wavefront correction by a deformable mirror. The code allows optimizing actuator array geometry on the square-shaped piston driven push/pull continuous facesheet deformable mirror. .

With defined actuator array geometry, the deformable mirror surface shape is approximated by a superposition of influence functions. The influence functions are calculated as a solution of the plate equation calculated by PDE solver. The optimal surface shape is then obtained by least squares method.

The code allows setting arbitrary actuator array geometry. We have corrected the simulated output wavefront of Hilase multi-slab laser system by using several actuator and mirror geometries. The output wavefront was obtained by calculating beam propagation in the multi-slab system that included thermal aberrations, Seidel optical aberrations and transmitted wavefront distortions on typical optical elements used in the system. The correction is analyzed in reference to mirror dimensions, beam trace position with respect to the actuators position and their amount. The effect of pre-correction with additional deformable mirror is also discussed and evaluated. An overview of the most promising cases is presented.

According to these optimization results, the wavefront of the 100 J multi-slab laser system with peak-to-valley value around 9? can be corrected to less than ?/10 with standard deformable mirrors that have only 49 actuators. The wavefront quality further improves below ?/20 if denser actuator arrays are used in the simulations. Experimental verification of some of these calculations is also investigated.

8780-38, Session PS

Novel method of single shot M2 measurement for high energy laser pulses in the near-infrared region

Siva Sankar Nagisetty, Taisuke Miura, Akira Endo, Tomas Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

For laser applications in industries, it is inevitable to have a good beam quality and that is why analysis of the laser beam parameter M2 is the critical matter. Since the principle of M2 measurement is to scan the beam diameters discretely along with propagation direction, relatively long measurement time is required which is not suitable for pulsed light sources. Although the single-shot M2 measurement by employing the multiple detectors or the wavefront measurement have been established, the multiple detector method limits the number of beam diameter samples, which is not enough to calculate M2 value precisely. And conventional wavefront sensors are difficult to evaluate the beam with large M2 value that has large wavefront distortion.

Bearing in mind the need, we are developing a novel procedure of single shot M2 measurement based on a photosensitive glass. The measurement system consists of the photosensitive glass plate and the imaging camera with macro lens. When the pulsed laser beam focused into the cross-sectional direction of photosensitive glass plate instead of perpendicular direction, the visible fluorescence of the glass plate indicates the focusing property of the input beam. Then the visualized beam propagation in the glass is imaged precisely using a high-resolution camera. And the beam diameters around beam waist can be analyzed. This technique allows the possibility of monitoring the beam quality in real time, in both continuous and pulsed operation.

The measurement results using this method and the comparison with conventional scan type systems will be discussed in the presentation.

8780-39, Session PS

Simple measurement of picosecond pulses at wavelengths above 1 micron

Martin Smrz, Taisuke Miura, Akira Endo, Tomas Mocek, Petr Straka, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

Ultrashort laser pulse measurements are often based on a time-domain or spectral-domain autocorrelation. The analyzed laser beam is usually divided into two beams which are mutually delayed and combined again. An optical signal, for example a second-order autocorrelation or a spectrogram, enabling a numerical or even analytical determination of a pulse length or full pulse retrieval is generated in the next step in a nonlinear optical medium. In addition to interferometric and multi-beam techniques, non-interferometric single-beam measuring techniques using an acousto-optic pulse shaper (MIIPS) or even only a dispersive delay line (Dispersoscopy) and a second harmonic generation crystal were proposed.

Dispersoscopy as it was firstly presented is based on a simple modulation of the pulse spectral phase using a pair of dispersive optical prisms or a simple set of glass plates instead of an interferometer or an acousto-optic modulator, and a nonlinear optical medium working as a time gate (e.g. a second harmonic generation crystal). Assuming a simple shape of the pulse being measured, the technique allows an analytic reconstruction of ultrashort pulses reaching the 15fs bandwidth limit. The full numerical spectral phase retrieval of general laser pulses is also possible.

On the other hand, dispersoscopy was proposed for broadband pulses of a Ti:saphire laser oscillator and has never been tested in different spectral ranges or on narrow band sub-picosecond pulses. This modification requires design of a new dispersive delay line which would sufficiently influence a temporal shape of the femtosecond pulse, i.e. its dispersion range and tunability has to be much broader than for broadband sub-20- femtosecond pulses.

We designed such a dispersoscope for measurement of sub picosecond pulses of an Yb:YAG regenerative amplifier generating radiation at the wavelength 1030nm. It is consisted of a dispersive delay line in a form of a diffraction grating based pulse stretcher with a ratio of the stretched and the bandwidth limited pulse in the range from -100 to 100 and it is followed by a second harmonic generation crystal (BBO).

We also plan to modify the device for measurement of picosecond pulses having their mid-wavelength in the range between 2 and 3 micrometers.

The detailed design of this dispersoscope, the latest experimental results verifying it, and essential modification for measurements at the wavelength 2-3um will be presented.

This work benefitted from the support of the Czech Republic's Ministry of Education, Youth and Sports to the HiLASE (CZ.1.05/2.1.00/01.0027) and DPSSLasers (CZ.1.07/2.3.00/20.0143) projects co-financed from the European Regional Development Fund.

8780-50, Session 11

From atomic to subatomic worlds: science and applications *(Keynote Presentation)*

Gérard A. Mourou, IZEST, Ecole Nationale Supérieure de Techniques Avancées (France)

No Abstract Available

8780-51, Session 11

On the extreme field limits in the high power laser matter interactions *(Invited Paper)*

Sergei Bulanov, Japan Atomic Energy Agency (Japan); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

We discuss the interaction of intense laser pulses with ultrarelativistic electron bunches and the collision of two or more intense laser pulses for studying extreme field limits in the nonlinear interaction of electromagnetic waves. In the regimes of dominant radiation reaction, powerful emission of ultra short high brightness gamma-ray pulses occurs. An electron positron pair creation from vacuum in the 3D electromagnetic configurations is considered. High intensity colliding laser pulses can create abundant electron-positron pair plasma, which can scatter the incoming electromagnetic waves. This process can prevent one from reaching the critical field of quantum electrodynamics at which vacuum breakdown and polarization occur. It is shown that the effects of radiation friction and the electron-positron avalanche development in vacuum depend on the electromagnetic wave polarization

8780-53, Session 11

Large-scale simulations of laser-plasma interactio: state of the art and next steps *(Invited Paper)*

Michael Bussmann, Heiko Burau, René Widera, Axel Hübl, Richard Pausch, Alexander Debus, Thomas Kluge, Ulrich Schramm, Thomas E. Cowan, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany); Felix Schmitt, NVIDIA Corp. (United States); Guido Juckeland, Wolfgang Nagel, Technische Univ. Dresden (Germany)

We present new results on PIConGPU, a GPGPU implementation of a relativistic 3D3V particle-in-cell implementation. We show weak and strong scalings for PIConGPU on large GPU clusters and discuss the techniques used to achieve such scalability.

We furthermore introduce new physics and analysis modules added to PIConGPU that have previously not been seen in laser-plasma interaction simulations. The new analysis modules help to better conduct large parameter surveys and increase the usability of the code. One of the special features of these analysis models is that all of them are in-memory and thus allow for live generation of simulation videos at frames per second time step rates. The new physics modules focus on the generation of radiation during the laser-plasma interaction and the inter-particle interactions.

We finally discuss new techniques to scale PIConGPU and other particle-in-cell codes to Exaflop performance and the possible benefits of such extreme scaling performance.

8780-54, Session 11

TBA *(Invited Paper)*

Mattias Marklund, Umeå Univ. (Sweden)

No Abstract Available

8780-55, Session 11

On the path to pair production: self-consistent multidimensional PIC modeling

Thomas Grismayer, Joana L. Martins, Univ. Técnica de Lisboa (Portugal); Ricardo A. Fonseca, Univ. Técnica de Lisboa (Portugal) and Univ. de Lisboa (Portugal); Luis O. Silva, Univ. Técnica de Lisboa (Portugal)

The availability of powerful lights sources offers in principle new possibilities for investigation of various quantum processes. Peak intensities up to 10^22 W/cm^2 are already available in some laser facilities and even greater intensities should be attainable with the development of ELI. The study of quantum effects in a very large electromagnetic wave field opens possibilities of obtaining new informations about the nature of these interactions in non perturbative regimes and of the dependences of these quantum processes on the field strength, frequency and polarization (parameters which can be varied in experiments).

Among various quantum phenomena, electron-positron pair production, at the focus of an intense laser, is currently a topic of considerable interest. As is typical for particle scattering experiments, many different processes may contribute to the final yields of pairs. Out of the possible mechanisms, pair production seeded by an electron is likely to be the most dominant. This process comes in two forms: a single step process, in which the intermediate photon is virtual (trident), and a two step process, in which non linear Compton scattering produces a real photon from the incoming electron and this real photon then goes on to create a pair via stimulated pair production (Breit-Wheeler).

In this work, we include theses processes in a massively parallel PIC code (using the Osiris 2.0 framework). Our approach in numerical modeling is focused on implementing in a self-consistent manner and multi-dimensions the interaction of the intense fields with the plasma dynamics while neglecting pair production in vacuum by Schwinger field and single pair annihilation. The dynamics of the electrons, ions, positrons, hard photons and the EM fields are calculated self-consistently by the standard PIC technique whereas the emissions of hard photons (QED radiation reaction) and pair production are computed by the Monte-Carlo method. We illustrate the numerical model by providing examples of several scenarios, that are likely to produce pairs, such as electromagnetic showers in static magnetic field, QED cascading in the head-on interaction of an electron beam with an intense laser and with multiple colliding pulses.

8780-56, Session 11

Effect of the radiation reaction in classical regimes of ultra-strong electromagnetic fields in plasmas

Remi Capdessus, Emmanuel d'Humières, Vladimir T. Tikhonchuk, Univ. Bordeaux 1 (France)

Radiation losses of electrons in ultra-intense laser fields constitute a process of major importance when considering laser-matter interaction at intensities of the order of and above 10?? W/cm?.

Radiation losses can strongly modify the electron (and in turns

ion) dynamics, and are associated with intense and directional emission of high energy photons. Accounting for such effects is therefore necessary to get a correct modeling of, e.g. electron and ion acceleration and creation of secondary photon sources at the forthcoming ultra-high power laser facilities. To account for radiation losses in the particle-in-cell code PICLS, we have introduced the radiation friction force obtained by Sokolov using a renormalized Lorentz-Abraham-Dirac model. The associated angular and energy spectra of the radiated high-energy photons are also computed. In this talk, we will present a study of the effect of radiation friction on the electron and ion dynamics in various regimes of ion acceleration. The angular and energy spectra of high-energy photons is discussed for different laser plasma interaction regimes. Secondly, the study of the development of a collisonless shock using an ultra intense laser field, in the context of laboratory astrophysics is discussed. The influence of the radiation reaction on the plasma dynamics and on spectra of the radiated high energy photons generated by the hot electrons is shown. Finally, a kinetic theory taking account for the radiation reaction and using the Sokolov's equations has been developed. The influence of the radiation reaction on the dispersion equation is especially shown.

8780-72, Session 11

Multiscale simulation of laser driven electron-positron-photon plasma

Nina Elkina, Ludwig-Maximilians-Univ. München (Germany)

Due to the prominent recent progress and perspectives (ELI, HiPER) in development of of the ultra-high power laser facilities worldwide it becomes urgently demanded to develop the complete theoretical and numerical frameworks to study quantum electrodynamic high-energy processes in laser driven plasma.

The problem to model such plasma is twofold. First, it is necessary to derive dual kinetic/field description for of the electromagnetic field by splitting it into classical (plasmons) and quantum (photons) counterparts.

In our model very high energy photons are treated in terms of quasiclassical distribution functions in the classical phase space, whereas the soft photons are described by the Maxwell equations.

Secondly, we are confronted with the problem of cross-scale coupling between large scale collective plasma processes and small scale dominated by elementary quantum effects. The idea to employ an adaptive mesh refinement comes up naturally.

However, incorporation of the adaptive meshes in computational plasma physics stumbles upon a number of difficulties associated with the mathematical structure of governing equations. We review major numerical challenges of multi-scale simulation of QED plasma and present a new code for multi-scale simulation of laser driven electron-positron-photon cascades.

8780-57, Session 12

Secondary source generation using 30-fs, PW Ti:sapphire laser (PULSER) *(Invited Paper)*

Tae Moon Jeong, APRI-GIST (Korea, Republic of)

The high-energy charged particles (proton and electron) and high energy photon (X-ray and gamma-ray) have substantial applications in the various disciplines such as bio-medical imaging, nano-technology, and atto-second science. The femtosecond (fs) petawatt (PW) Ti:sapphire laser, compared to the conventional accelerator, is a relatively compact system generating high-energy charged particles and high energy photon. Recently, a 30-fs, 1.5-PW CPA Ti:sapphire laser system (PULSER) operating at 0.1-Hz repetition rate has been constructed for applications in high field physics and atto-second science at Advanced Photonics Research Institute (APRI), GIST. When focusing the PW laser pulses with an f/3.5 focusing optic, the peak intensity can reach at ~ 4 x 1021 W/cm2. The experiments on the acceleration of electrons and protons using 30-fs, PW laser pulses have been performed. In the electron acceleration experiment, the electron beam having a maximum energy of about 3 GeV was observed with an injection scheme. In the proton experiment, we could accelerate proton beams up to 45 MeV from a 10-nm-thin polymer target. The intensity scaling clearly indicated the transition of accelerating mechanism from the target normal sheath acceleration (TNSA) to radiation pressure acceleration (RPA). The high harmonic generation experiment from a solid target is being prepared to produce ultrashort x-ray source in the water-window regime. The fs, PW laser is highly promising in producing unprecedented secondary sources and understanding novel mechanism of physical processes.

8780-58, Session 12

Coherent synchrotron emission from nanofoil targets *(Invited Paper)*

Matthew Zepf, Queen's Univ. Belfast (United Kingdom)

No Abstract Available

8780-59, Session 12

Adaptive attosecond pulse control with synthesized light *(Invited Paper)*

Balázs Bódi, Wigner Research Ctr. for Physics of the H.A.S. (Hungary); Emeric Balogh, Univ. of Szeged (Hungary); Valer Tosa, National Institute for Research and Development of Isotopic and Molecular Technologies (Romania); Katalin Varju, Univ. of Szeged (Hungary); Peter Dombi, Wigner Research Ctr. for Physics of the H.A.S. (Hungary) and Max-Planck-Institut für Qantenoptik (Germany)

It is known that the prerequisite for the generation of pulses for attosecond methods is a precise control over the driver wave of the high harmonic generation (HHG) process, typically lying in the near-infrared domain of the spectrum. The most crucial control parameters, such as pulse length and the carrier-envelope phase of laser pulses were identified an brought under control early on in the development of attosecond science. A significant step further is the ability to synthesize single-cycle light transients, as demonstrated recently. Thus, it is now possible to produce a variety of arbitrary attosecond driver waveforms with the help of high-power supercontinuum generation in hollow core fibers and a subsequent ultrabroad-band 3-channel interferometer which effectively synthesizes broadband, single-cycle light pulses from a UV-visible (350-520 nm), a visible (520-700 nm) and an infrared (700-1050 nm) channel.

Therefore, in the current work, we aim at the theoretical investigation of the capabilities of such synthesized light transients in terms of attosecond pulse generation. In order to explore the full potential of this method with a versatile numerical tool, we chose to optimize over multiple parameters of the broadband pulse synthesis interferometer in order to optimize attosecond pulse generation and shaping in the extreme ultraviolet domain. For the investigation of this phenomenon, we determined possible synthesized light waveforms by modelling the experimentally realized 3 interferometer channels. With these driver waveforms, we modelled the high harmonic generation process in Ne gas by calculating the single atom dipole response (by computing the Lewenstein integral) and extracting high harmonic spectra. With the XUV amplitudes and phases at hand, attosecond waveforms were determined.

Since in the broadband interferometer one can adjust the amplitudes, phases and even the delays of the individual channels, there are a number of free parameters at hand. Their optimization was carried out by means of a genetic algorithm in order to match a desired attosecond pulse shape (being, for example the shortest possible pulse or an attosecond double pulse with a non-trivial delay). By properly adjusting the parameters of the genetic algorithm (initial population, population size, crossover and mutation rates etc.), it proved to converge to the desired solutions within 80-90 generations.

With these tools, we demonstrated a route toward versatile attosecond pulse control by shaping the driver pulses with the help of a broadband interferometer synthesizing light pulses. The potential of this method is shown by the generation of a 45-asec single attosecond pulse and attosecond double pulses having adjustable delay between 300 and 1000 asec (only by reshaping the driver waveform). In order to extend

the applicability of the method, we also study, how the chirp of the attosecond pulses can be tailored to a preset value. We carry out further numerical studies to analyse phase matching effects, arising in the macroscopic medium, using a propagation model of the driver/XUV pulses. The proposed adaptive method offers a tool for tailoring attosecond pulse generation through the control of easily accessible experimental parameters in a broadband 3-channel interferometer already at hand.

8780-60, Session 13

ELI-Beamlines status *(Invited Paper)*

Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

No Abstract Available

8780-61, Session 13

Realisation and status of the European XFEL facility *(Invited Paper)*

Thomas Tschentscher, European XFEL GmbH (Germany)

Construction of the European XFEL is at full pace with most underground buildings completed and surface buildings progressing. The construction of the 17.5 GeV super-conducting electron accelerator is in full progress and first components have arrived and are tested for performance. The layout of the x-ray transport systems and the six scientific instruments is progressing, too. The expected performance parameters recently have been updated using the results from photo-injector tests and measurements at the Linac Coherent light Source at SLAC, U.S.A. The new parameter range foresees delivery of FEL radiation with photon energies from 0.26 to 25 keV with durations ranging between 2 and 100 fs. In addition, the implementation of seeding schemes is prepared which should allow to use fully coherent hard x-ray pulses for applications. In the talk an overview of the current status, the layout and applications of the scientific instruments, and some outlook to the operation of the facility are given.

8780-62, Session 13

ELI-ALPS: The attosecond ELI infrastructure *(Invited Paper)*

Károly Osvay, ELI-Hu Nkft. (Hungary) and University of Szeged (Hungary); Charalambidis Dimitris, ELI-Hu Nkft. (Hungary) and FORTH, Crete (Greece); Zsolt Diveki, ELI-Hu Nkft. (Hungary) and Imperial College, London (United Kingdom); Peter Dombi, ELI-Hu Nkft. (Hungary) and Wigner Research Centre for Phyics, Budapest (Hungary) and Max-Planck-Institut für Quantenoptik, Garching (Germany); Jozsef A Fulop, ELI-Hu Nkft. (Hungary) and MTA-PTE Research Group on THz, Pecs (Hungary); Mikhail P Kalashnikov, ELI-Hu Nkft. (Hungary) and Max-Born-Institut, Berlin (Germany); Rodrigo Lopez-Martens, ELI-Hu Nkft. (Hungary) and Laboratoire d'Optique Appliquee, Palaiseau (France); Ervin Racz, ELI-Hu Nkft. (Hungary) and Obuda University, Budapest (Hungary)

The Attosecond Light Pulse Source (ALPS) facility of the pan-European Extreme Light Infrastructure (ELI) project is designed to realise a laser based research infrastructure in which light pulses of few optical cycles are generated and used for basic and applied research. The pulse duration can be as short as a few tens of attosecond (1 as = 10-18 s). Such extremely short pulses are necessary for observing elementary processes in atoms and molecules, as well as to reveal physical events of light-matter interactions in solids on the lementary scale.

The ELI-ALPS infrastructure is based on three main laser sources, operating in different regimes of repetition rate and peak power. All three light sources deliver pulses with unique parameters: unparalleled fluxes, extreme broad bandwidths and sub-cycle control of the generated fields. The high repetition rate (HR) system delivers TW peak power, < 5 fs pulses at 100 kHz. The 1 kHz repetition rate future single cycle (SYLOS) system provides 20 TW pulses with a pulse duration of < 5 fs. The petawatt class high field (HF) laser would operate at 5-10 Hz repetition rate with shorter than 15 fs pulse durations. This exceptional performance will give way to a set of secondary sources with incomparable characteristics, including light sources ranging from the THz to the X-ray spectral ranges, and particle sources. The unique source parameters will enable intriguing new insight in valence and core electron science, attosecond imaging in 4D, relativistic interaction, manipulation of matter by intense THz fields, and various biological, medical, and industrial applications.

The project will be realized in two phases. In Phase 1, expected to be concluded by the end of 2015, construction of the technology and auxiliary buildings will be accomplished, the major part of the scientific equipment will be put in place and the laser systems will operate. In Phase 2 installation of the scientific technology will be completed e.g. obtaining isolated attosecond pulses with unprecedented peak-power. The envisaged full research capacity will be available from 2018 on. Research to be carried out at ELI-ALPS may well create breakthroughs in the fields of physics, chemistry, life, and material sciences.

8780-63, Session 13

Extreme Light Infrastructure-Nuclear Physics (ELI-NP): present status and perspectives *(Invited Paper)*

Nicolae V. Zamfir, Horia Hulubei National Institute of Physics and Nuclear Engineering (Romania)

No Abstract Available

8780-91, Session 13

Advanced Laser Light Source (ALLS) facility: recent achievements and future perspectives (Invited Paper)

Jean-Claude Kieffer, Institut National de la Recherche Scientifique (Canada)

No abstract available

8780-64, Session 14

Dense electron-positron plasmas generated by 10PW lasers in the QED-plasma regime *(Invited Paper)*

Christopher P. Ridgers, Univ. of Oxford (United Kingdom)

Electron-positron plasmas are a prominent feature of the high energy Universe. In the relativistic winds from pulsars and black holes it is thought that non-linear quantum electrodynamics (QED) processes cause electromagnetic energy to cascade into an e-e+ plasma. We show that next-generation 10PW lasers, available in the next few years, will generate such a high density of pairs that they create a micro-laboratory for the first experimental study of a similarly generated e-e+ plasma. In the first simulations of a 10PW laser striking a solid we demonstrate the production of a pure electron-positron plasma of density 10^26/m^3. This is seven orders of magnitude denser than currently achievable in the laboratory and is comparable to the critical density for commonly used lasers, marking a step change to collective e-e+ plasma behaviour. Furthermore, a new ultra-efficient laser-absorption mechanism converts 35% of the laser energy to a burst of gamma-rays of intensity 10^22W/cm^2, potentially the most intense gamma-ray source available in the laboratory. This absorption results in a strong feedback between both pair and gamma-ray production and classical plasma physics leading to a new physical regime of QED-plasma physics. In this new regime the standard particle-in-cell (PIC) simulation approach, which has been the dominant kinetic simulation tool in plasma physics for 50 years, is inadequate. We have developed a new approach (QED-PIC) which will provide a powerful

new modelling tool essential to the future advancement of the field of high intensity laser-plasma interactions.

8780-65, Session 14

Nature of the strong field capabilities of lasers *(Invited Paper)*

Howard R. Reiss, American Univ. (United States) and Max-Born-Institut für Nichtlineare Optik und Kurzzeitspektroskopie (Germany)

Much discussion about effects of lasers of extremely high intensity has been in terms of tunneling and the “Schwinger Limit”, which is the field intensity for breakdown of the vacuum into copious production of electron-positron pairs. There is a difficulty in many of these proposals that follows from confusion between transverse fields and longitudinal fields. Lasers produce transverse fields, whereas tunneling phenomena, including the Schwinger Limit, are limited to longitudinal fields. The distinction between transverse and longitudinal fields is basic for electrodynamics and for laboratory consequences. In electrodynamics, transverse fields have the unique property that they propagate indefinitely without any inputs from sources or currents. Longitudinal fields cannot exist without continuing contributions from external sources. Many proposed applications of lasers of very high intensity apply to phenomena that follow only from tunneling, and thus relate to an entirely different domain in electrodynamics than can be accessed with laser fields. The notion exists that tunneling phenomena are a low-frequency limit of laser-induced processes. A specific counter-indication is that the ponderomotive potential experienced of a charged particle in a laser field is proportional to the inverse square of the field frequency. These assertions will be demonstrated mathematically and in terms of the very informative frequency-vs.-intensity diagrams that make clear the limitations of the Goeppert-Mayer gauge transformation of atomic physics. These diagrams show where and why this correspondence fails. This failure is most important as the frequency of the field becomes very low. A result is the clear demonstration that the low-frequency limit of a plane wave field is not a static electric field. Vacuum phenomena like pair production do not require the achievement of the Schwinger Limit.

8780-66, Session 14

Kapitza-Dirac effect and nonresonant nonlinear quantum interaction of laser and electron beams

Heinrich Hora, The Univ. of New South Wales (Australia); Peter H. Handel, Univ. of Missouri-St. Louis (United States)

The direct experimental demonstration1 of the Kapitza-Dirac effect2 for scattering of an electron beam when crossing a laser beam by standing wave nodes and antinodes was finally possible by using sufficiently high laser intensities. The generalization with using interacting media located in the crossing area led to a non-resonance process including nonlinearity as an essential mechanism3. The non-resonance is considered as an access for clarifications on fundamental presumptions for basing quantum theory on observable objects as the energy levels in quantum systems introduced initially by Heisenberg 1925. The processes are connected with 1/f noise theory4 were the generalization to coherent states was necessary3,5. This is then related to such high laser intensities with same photon density as the electron density is in condensed targets6 up to such extreme laser intensities where one photon is located per cube of the Compton wave length.

1. Freimund D.L., Aflatooni K. & Batelaan H. Observation of the Kapitza-Dirac effect, Nature, 413, 142-143 (2001)

2. Kapitza P.L., & Dirac P.A.M., The reflection of electrons from standing light waves. Proc. Camb. Phil. Soc., 29, 297-300 (1933)

3. Hora H., &. Handel P.H. New Experiments and theoretical development of the Quantum Modulation of Electrons. Advances in Electronics and Electron Physics, Hawkes P.W. ed. (Acad. Press, New York, 1987) 69, p.55-113.

4. P.H. Handel: “Quantum Approach to 1/f Noise”, Phys. Rev. A22, p. 745 (1980).

5. van der Ziel A., van Rheenen A.D. & A.N. Birbas A.N. Extensions of Handel’s 1/f Noise Equations, Phys. Rev. B40, 1806-1809 (1989).

6. Boreham B.W., Hora H. & Bolton B.R. Photon Density and Correspondence Principle of Electromagnetic Interaction, Laser Interaction and Related Plasma Phenomena, G.H. Miley and S. Nakai eds., AIP Proceed. No. 369 (Am. Inst. Phys., New York, 1995) p.1234-1239.

8780-67, Session 14

Laser leptonics with LMJ-PETAL and ELI Beamlines

Ladislav Drska, Czech Technical Univ. in Prague (Czech Republic); Emmanuel d’Humières, Univ. Bordeaux 1 (France); Vaclav Hanus, Milan Sinor, Czech Technical Univ. in Prague (Czech Republic); Vladimir T. Tikhonchuk, Univ. Bordeaux 1 (France)

This contribution is intended to present information on the ongoing study of potential coordinated research activities in exotic matter physics for new big high-intensity laser facilities - LMJ-PETAL and ELI (esp. Beamlines pillar). Their parameters allow identify several branches of exotic matter physics with reasonable chances for positive results in the foreseeable period. Synergistic approach to the exploitation of these unique systems poses a great challenge.

(1) Laser Leptonics, Physics and Applications: Production of unconventional tertiary particles, esp. leptons (positrons, muons, neutrinos) via intense laser interaction seems to be one of the realistic aims. Focused intensities (FI) in the range 10^20 – 10^24 W/cm^2 enable to study various mechanisms of lepton generation (electromagnetic and nuclear processes) and construct particle sources with parameters suitable both for basic research and future sophisticated applications.

(2) LMJ-PETAL & ELI Beamlines Synergy: In the first-phase research, activities mainly with FI < 10^22 W/cm^2 are considered. A comparison of ps (PETAL) and strongly sub-ps (ELI) regimes could be possible. In the contribution, some results of computer simulations of positron generation using PIC and MC codes (PICLS, FLUKA, etc.) will be introduced. Quantification of neutron contamination will be also included. Potential technical solutions for applicable sources will be judged. Preliminary analysis of selected studies in fundamental physics using these sources will be presented (positron astrophysics processes, positronium production and BEC, etc.). The possibility of proof-of-principle experiments in muon generation using LWFA concepts will be also indicated.

(3) High-Intensity Regime Studies Concepts: In the next research phase, the availability of intensity interval (10^22, 10^24 / maybe >10^24 W/cm^2) is supposed. In this presentation, after a short overview of potential studies in radiation-dominated regime, two issues will be discussed : electron-positron pairs as a signature of strong QED effects / feasibility and applicability of positron sources driven with extreme intensities. Problems of simulations and technical issues of particle experiments in this area will be outlined. Conditions for reasonably effective laser-based generation of muons will be judged. Possible new / meaningful applications of laser-produced muons in basic physics using the ELI facility will be searched (complementarity of laser / accelerator muonics, invisible decay of muonium, etc.).

In conclusion, prospective exploitation of laser-driven positron / muon sources and related know-how beyond the basic physics research will be shortly mentioned, potential novel high-tech applications will be stressed (positron diagnostics in ion beam therapy, massive antimatter accumulation, fast muon radiography / tomography , etc.) . The key role of new concepts of high-average-power laser systems for real applied leptonics will be highlighted.

8780-68, Session 14

Full-scale 3D PIC simulations in the radiation reaction dominated regime with ELI lasers

Marija Vranic, Joana L. Martins, Jorge M. Vieira, Univ. Técnica de Lisboa (Portugal); Ricardo A. Fonseca, Univ. Técnica de Lisboa (Portugal) and Univ. de Lisboa (Portugal); Luis O. Silva, Univ. Técnica de Lisboa (Portugal)

Radiation reaction is relevant for plasma dynamics in astrophysical and laboratory scenarios when the radiated energy is comparable to the total particle energy. However, the experimental confirmation for the domain of validity of classical radiation reaction theory, as well as demonstration of the radiation reaction process is still missing. The thresholds for the transition from the classical to the quantum radiation reaction dominated regime are also under a strong scientific debate. We present a theoretical and numerical study of the conditions that would provide an answer to some of these questions in an all-optical configuration with laser systems available today (i.e. I~10^21 W/cm2). We performed 3-dimensional full-scale particle-in-cell OSIRIS simulations of laser wakefield accelerators accounting for the radiation reaction, allowing the electron beam to interact with an intense laser after it leaves the plasma. We discuss experimentally measurable signatures of radiation reaction both in the electron spectra, and the backscattered laser photons. Electron energy loss of 40% due to the radiation reaction was obtained using a laser of intensity 10^21 W/cm2 and an LWFA electron beam of 1 GeV. The theoretical predictions for energy loss are in excellent agreement with the simulation results for various configurations presented.

In addition, we show that the transition from the radiation reaction dominated to QED regime can be explored experimentally with ELI relevant laser parameters.

8780-69, Session 14

The radiation reaction effect in ultra intense laser interactions with foils: laser absorption

Martin Jirka, Ondrej Klimo, Jirí Limpouch, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Martin Masek, Institute of Physics (Czech Republic); Georg Korn, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Michael Bussmann, Helmholtz-Zentrum Dresden-Rossendorf e. V. (Germany)

Since the radiation reaction effect on electron propagation is very small in most cases, it can be usually neglected and the Lorentz force equation can be applied. However, ultra-intense lasers with normalized vector potential of the order of 100 can accelerate electrons to relativistic velocities with very high gamma factor. When the electron is accelerated to such high velocities the amount of emitted radiation can become large and radiation damping should be considered. This work studies the influence of the radiation reaction force on the interaction of an ultra-intense laser pulse with a foil target using 1D and 2D PIC simulations. It is shown that above a certain threshold, the laser energy absorption in the foil is higher due to the radiation friction force. The absorbed energy is partially transferred to ions and partially reemitted in the form of higher energy photons.

8780-70, Session 14

Nonlinear double Compton scattering in the ultrarelativistic quantum regime

Felix Mackenroth, Max-Planck-Institut f ur Kernphysik (Germany); Antonino Di Piazza, Max-Planck-Institut für Kernphysik (Germany)

The interaction between an electron and a laser field may become nonlinear for ultra-high laser intensities [1]. In this regime a wide class of new phenomena becomes important such as a dynamical mass shift [2] or the emission of photons upon the absorption of several laser mode photons. The simplest process of the latter class is single photon emission, which was labeled nonlinear single Compton scattering (NSCS). In the recent past there has been an increasing interest in such nonlinear scattering processes and several QED analyses of NSCS emission spectra for an arbitrary temporal shape of the scattering laser field were performed [3]. Eventually the understanding of NSCS can pave the road towards technical applications such as a viable determination scheme for the carrier-envelope phase of ultra-intense few-cycle laser pulses [4], which is impossible with present measurement techniques.

Beyond NSCS quantum electrodynamics also predicts the simultaneous emission of more than one photon. The simplest effect of this type is the emission of two photons [5], labeled nonlinear double Compton scattering (NDCS). We present a detailed analysis of NDCS in an ultra-strong laser field taking the effects of the laser into account exactly and allowing for an arbitrary temporal field shape. We show numerical spectra for a parameter regime where nonlinear and quantum effects such as photon recoil significantly affect the emission pattern. In this regime, due to recoil, the energies of the emitted photons become correlated. This dependence is explained in terms of a semiclassical model, based on the possibility of assigning separate classical trajectories to the electron in the laser field before and after each quantum photon emission [6]. By virtue of the developed model we identify an experimentally feasible detection scheme for NDCS in the full quantum regime, which is accessible with already available electron accelerator and laser technology.

8780-71, Session 14

Computational relativistic quantum dynamics and its application to relativistic tunneling and Kapitza-Dirac scattering

Heiko Bauke, Michael Klaiber, Enderalp Yakaboylu, Karen Z. Hatsagortsyan, Sven Arens, Carsten Müller, Christoph H. Keitel, Max-Planck-Institut für Kernphysik (Germany)

With present-day strong lasers providing intensities of the order of 1022W=cm2 and employing highly charged ions, the regime of relativistic quantum dynamics of strong field processes becomes accessible. The time-dependent Dirac equation and the time-dependent Klein-Gordon equation form the basis for a theoretical description of relativistic quantum dynamics. Deducing analytical solutions of these equations, however, poses a major problem. Thus, ultra short laser-matter interactions at relativistic intensities require numerical approaches via computer simulations.

For this purpose, methods from nonrelativistic computational quantum dynamics may be transferred into the relativistic regime. However, also new and better methods are needed because relativistic computational quantum dynamics is much more demanding than its nonrelativistic sibling. In this contribution, we survey the challenges of numerical time-dependent relativistic quantum dynamics and present approaches to master these challenges by smart numerical algorithms [1, 2], by high-performance implementations on parallel architectures, including cluster computers and graphics processing cards [1, 3, 4], and by casting a quantum system's mathematical description by physical insights into a form that is beneficial for numerical methods [5]. The new methods of computational relativistic quantum dynamics are likely to be beneficial for the emerging field of computational quantum electrodynamics [6].

Some applications of numerical relativistic time-dependent quantum dynamics will be highlighted.

For example, the tunneling dynamics in relativistic strong-field ionization may be investigated by means of numerical (and analytical) methods to develop an intuitive picture for the relativistic tunneling regime [7]. It is demonstrated that the tunneling picture applies also in the relativistic regime by introducing position dependent energy levels. The time for the formation of momentum components of the ionized electron wave packet (Keldysh time) and the time interval which the electron wave packet spends inside the barrier (Eisenbud-Wigner-

Smith time delay) are identified as the two characteristic time scales of relativistic tunnel ion-ization.

The Keldysh time can be related to a momentum shift that is shown to be present in the ionization spectrum at the detector and, therefore, observable experimentally.

We also apply computational relativistic quantum dynamics to study

Kapitza-Dirac scattering of electrons by light [8]. In particular, we demonstrate that inelastic scattering processes involving a small odd number of photons are intrinsically relativistic and involve periodic oscillations of the electron's spin degree of freedom. For certain experimental setups, the scattering probability differs significantly for spin-zero and spin-half particles highlighting the role of the spin degree of freedom for this process.

[1] Matthias Ruf, Heiko Bauke and Christoph H. Keitel; Journal of Computational Physics, vol. 228, nr. 24, pp. 9092-9106 (2009)

[2] Frederick Blumenthal and Heiko Bauke; Journal of Computational Physics, vol. 231, nr. 2, pp. 454-464 (2012)

[3] Heiko Bauke and Christoph H. Keitel; Computer Physics Communications, vol. 182, nr. 12, pp. 2454-2463 (2011)

[4] Heiko Bauke and Stephan Mertens; «Cluster Computing», Springer (2006)

[5] Heiko Bauke and Christoph H. Keitel; Physical Review E, vol. 80, nr. 1, article 016706 (2009)

[6] R. E.Wagner, M. R.Ware, B. T. Shields, Q. Su, and R. Grobe; Physical Review Letters, vol. 106, nr. 2, article 023601 (2011)

[7] Michael Klaiber, Enderalp Yakaboylu, Heiko Bauke, Karen Z. Hatsagortsyan, and Christoph H. Keitel; Under-the-barrier dynamics in laser-induced relativistic tunneling; arXiv:1205.2004

[8] Sven Arens, Heiko Bauke, Christoph H. Keitel, and Carsten Müller; Physical Review Letters, vol. 109, nr. 4, article 043601 (2012)

8780-87, Session 14

Energy transfer in counter-propagating plasmas at sub-relativistic velocities

Vladimir T. Tikhonchuk, Remi Capdessus, Emmanuel d'Humières, Sophie Jequier, Stanley P. Davis, Univ. Bordeaux 1 (France)

Collisionless shocks are frequent events in the interstellar medium, they can also take place in inertial fusion targets where high energy ion beams interact with target plume plasma. The understanding of the processes is consequently important from a theoretical point of view and for laboratory laser--plasma interaction experiments. Large scale particle-in-cell simulations are widely used to give crucial informations on the shock evolution and the energy dissipation. They also give access to ion and electron particle and energy densities and electromagnetic fields, authorizing energy transfer analysis from the ions to electrons and fields.

In this communication, we consider interaction of two counter-propagating homogeneous sub-relativistic plasma beams with no external magnetic field applied. In numerical simulations performed with a particle-in-cell code three stages of evolution can be identified. The shock formation is initiated with development of the electron-ion Weibel-like micro-instabilities, followed by fast electron heating and ion deceleration and heating. We present a theoretical analysis of the instabilities development and nonlinear saturation to explore the origins of the heating and the magnetic field generation. Electrons are assumed relativistic and cold ions are counter-propagating with sub-relativistic velocities. The analysis is done in the center of mass frame, considering the Lorentz transformation for each beam from its own reference frame. From the dispersion relation, instability is characterized and dependence on the electron temperature and ion velocity is studied. The growth rate and the characteristic scales of instability are compared to simulation results. The role of quasi-static electric fields in the instability development and particle heating is discussed.

This approach provides a global view of the instabilities induced in the interaction process and generating collisionless energy transfer between ions and electrons.

8780-73, Session 15

Developments toward rep-rated multi-PW to exawatt lasers *(Invited Paper)*

Todd Ditmire, The Univ. of Texas at Austin (United States)

No Abstract Available

8780-74, Session 15

ELI-Beamlines laser systems: design options and status *(Invited Paper)*

Bedrich Rus, Pavel Bakule, Daniel Kramer, Jonathan T. Green, Jakub Novak, Martin Fibrich, Frantisek Batysta, P. Korous, Martin Laub, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

No Abstract Available

8780-76, Session 15

Technology development for multi-PW CPA and OPCPA based laser systems

Ian Musgrave, Alexis Boyle, John L. Collier, Robert J. Clarke, Robert Heathcote, Cristina Hernandez-Gomez, Chris J. Hooker, Marco Galimberti, Andrey Lyachev, Dave Neely, Peter A. Norreys, Bryn T. Parry, Rajeev P. Pattathil, Ian N. Ross, Waseem Shaikh, Yunxin Tang, Trevor B. Winstone, 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 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.

8780-77, Session 15

Design of kW level picosecond compressor of pump pulses for high power OPCPA

Pavel Bakule, Institute of Physics of the ASCR v.v.i. (Czech Republic); Jakub Novak, Daniel Kramer, P. Strkula, Efstratios Koutris, T. Base, Frantisek Batysta, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Jonathan T. Green, Institute of Physics of the ASCR. v.v.i. (Czech Republic); Bedrich Rus, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

No Abstract Available

8780-78, Session 15

DiPOLE: a scalable laser architecture for pumping multi-Hz PW systems

Klaus Ertel, Rutherford Appleton Lab. (United Kingdom)

No Abstract Available

8780-79, Session 15

Plasma mirrors and applications at relativistic intensities

David Neely, Rutherford Appleton Lab. (United Kingdom)

No Abstract Available

8780-80, Session 15

Requirements and test capabilities for the damage threshold of optical surfaces in the ELI-beamlines facility

Daniel Kramer, Rui Nuno Almeida De Sá Barros, Bedrich Rus, Jan Hrebicek, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Tomas Medrik, Univ. Palackého V Olomouci (Czech Republic); Efstratios Koutris, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

The ELI-beamlines project is expected to reach state of the art parameters in its laser systems. The Laser Induced Damage Threshold of the corresponding optical systems will have to sustain the expected fluences and repetition rates. The LIDT requirements for the ultrafast pulse compressors, vacuum transport mirrors and high average power optics are presented together with the current and planned capabilities for LIDT testing with a 25TW laser system at 800 and 1060nm.

8780-81, Session 15

Microtargetry for next generation PW-class lasers

Martin K. Tolley, Rutherford Appleton Lab. (United Kingdom)

No Abstract Available

8780-82, Session 15

Thin disk picosecond pump laser for jitter stabilized kHz OPCPA

Jakub Novak, Pavel Bakule, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Jonathan T. Green, Institute of Physics ASCR, v.v.i. (Czech Republic); Jan Hrebicek, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Jack Naylon, Institute of Physics ASCR, v.v.i. (Czech Republic); Tomas Mazanec, Michal Vitek, Bedrich Rus, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

No Abstract Available

8780-52, Session 16

Critical acceleration: probing elementary interactions in laser-electron scattering *(Invited Paper)*

Johann Rafelski, The Univ. of Arizona (United States)

REVIEW TALK: In collisions of ultra-intense laser-pulse with relativistic electrons, as well as in ultra relativistic heavy ion collisions at RHIC and at LHC it is possible to probe critical acceleration $a=mc^3/hbar$, an object related to Planck scales but not burdened by G_N. The behavior of a particle undergoing critical acceleration challenges the limits of the current understanding of basic interactions: little is known about this physics frontier; both classical and quantum physics will need further development in order to be able to address this newly accessible area of physics. In this lecture

I will review the foundations of current understanding of particles dynamics and inertia in presence of gravity, EM-fields and forces; and will discuss radiation reaction issues and possible theoretical extensions as well as the relation with quantum physics and strong field particle production phenomena. Examples will be presented showing differences in dynamics of relativistic electrons in strong laser fields comparing conventional Lorentz dynamics to radiation reaction dynamics.

8780-83, Session 16

Targets for electron acceleration with ELI laser beams *(Invited Paper)*

Nelson C. Lopes, Univ. Técnica de Lisboa (Portugal)

Laser-Plasma-Wakefield-Accelerators (LWFA) can produce ultra-short high-charge electron bunches in a compact setup being able to substitute much larger conventional machines in some applications and opening the way to new applications where the high current and compact size of the source play an important role. Among these applications will be the use of the electron beams in medical treatments or the secondary radiation produced by the electron beams in plasma wigglers or free-electron-lasers for high resolution imaging in the x-ray domain.

With ELI, a new class class of petawatt lasers will be available for driving LWFA's opening the possibility for electron beams with better quality, higher charge and higher energy as well as radiation brighter and more energetic. The scaling laws for LWFA indicate that for this type of lasers the acceleration lengths will scale to 2-5 cm for self-guiding self-injection and up to 2 meters for external-guiding for energy. Plasma channels for external guiding consist in a cylindrically

symmetric plasma structure with a parabolic radial density profile that can that provide the correct plasma density for acceleration in the optical axis and at same time keeps avoids the diffraction of the laser beam allowing the extension of the acceleration to the optimum length. With ELI lasers, the use of plasma channels in external guiding, with an adequate electron beam injection scheme, will result in electron bunches with energies above 4 GeV being able generate an x-ray beam that can be used for high-resolution imaging.

In this talk we will present results on the development of plasma sources for laser driven electron acceleration and their use at Astra-Gemini laser facility. We will discuss the limitations of the present plasma channels and the future developments to bring these structure closer to the parameters required by future PW class lasers.

8780-84, Session 16

Petascale simulations of laser plasma accelerators at ELI regimes *(Invited Paper)*

Ricardo A. Fonseca, Univ. Técnica de Lisboa (Portugal)

The extreme laser intensities achieved by PW-Class Lasers can generate tremendous accelerating fields, promising the development of a new generation of plasma based accelerators, capable of delivering high quality electron/ion beams for multiple applications. This development will rely heavily on numerical modeling for further understanding of the underlying physics and identification of optimal regimes. Fully relativistic particle-in-cell codes such as OSIRIS [1] have established themselves as the tool of choice for modeling these scenarios, but given the computational requirements of these algorithms detailed full scale 3D modeling of these scenarios require efficient use of state-of-the-art Petascale supercomputing systems throughout the full simulation. This requires not only efficient simulation algorithms, but also matching these algorithms to the computing hardware, ensuring both good parallel scalability to hundreds of thousands of computing cores, and high floating point efficiency at the single core level. We discuss new developments implemented in the OSIRIS framework to address these issues, ranging from multi-dimensional dynamic load balancing and hybrid distributed / shared memory parallelism to the vectorization of the PIC algorithm. The performance of these features is evaluated in Tier-0 computing systems, and we will present the results obtained focusing on numerical performance and efficiency of the solutions. We will also address different algorithms being used to allow for longer interaction lengths, for laser wakefield acceleration, and for overcritical laser interaction scenarios, for ion acceleration.

[1] R. A. Fonseca et al., Lect Note Comp Sci, vol. 2331, pp. 342-351, (2002)

8780-85, Session 16

Enhanced TNSA acceleration with 0.1-1 PW lasers

Daniele Margarone, Institute of Physics of the ASCR (Czech Republic); Ondrej Klimo, CTU (Czech Republic); I Jong Kim, APRI-GIST (Korea, Republic of); Jan Prokupek, Institute of Physics of the ASCR (Czech Republic); Jiri Limpouch, CTU (Czech Republic); Tae Moon Jeong, APRI-GIST (Korea, Republic of); Tomas Mocek, Institute of Physics of the ASCR (Czech Republic); Jan Psikal, CTU (Czech Republic); Hyung Taek Kim, APRI-GIST (Korea, Republic of); Jan Proska, CTU (Czech Republic); Kee Wan Nam, APRI-GIST (Korea, Republic of); Tadzio Levato, Institute of Physics of the ASCR (Czech Republic); Lucie Stolcova, CTU (Czech Republic); Seong Ku Lee, APRI-GIST (Korea, Republic of); Miroslav Krus, Institute of Physics of the ASCR (Czech Republic); Jae Hee Sung, Tae Jun Yu, APRI-GIST (Korea, Republic of); Georg Korn, Institute of Physics of the ASCR (Czech Republic)

The enhancement of laser-driven proton acceleration mechanism in TNSA regime has been demonstrated through the use of advanced nanostructured thin foils. The presence of a monolayer of polystyrene nanospheres on the target front-side has drastically enhanced the absorption of the incident laser beam, leading to a consequent increase in the maximum proton beam energy and total laser conversion efficiency. The experimental measurements have been carried out at the 100 TW and 1 PW laser systems available at the APRI-GIST facility. Experimental results and comparison with particle-in-cell numerical simulations are presented and discussed.

Ref: D. Margarone et al., Phys. Rev. Lett. 109 (2012) 234801.

8780-86, Session 16

Collective electron interaction at ultgrafast acceleration of plasma blocks *(Invited Paper)*

Heinrich Hora, The Univ. of New South Wales (Australia)

It took some time before it was realized that electrons in vacuum can be accelerated by laser beams due to nonlinear effects [1]. The mechanisms are now fully established for electrons and for ions in pure vacuum conditions where collective effects can be included only gradually for improvements. In contrast to this, the laser interaction with solids or plasmas with much higher than critical electron density were from the beginning including collective effects. One only had to distinguish from thermal pressure effects at low or modest laser intensities. First numerical results including the ponderomotive force as a nonlinear force fNL after correct dielectric formulation of Maxwells stress tensor for plasmas, resulted in the dominance of fNL for laser pulses of picoseconds duration and 1018 W/cm2 neodymium glass laser intensity. The acceleration of plasma blocks arrived 1978 at ultrahigh values above 1020 cm/s2 (see p. 179 of [2]). This could be measured not before 1996 by Sauerbrey using the Doppler effect [3] where a suppression of the pre-pulse had to be better than 108 to avoid relativistic self-focusing was necessary. Agreement with the earlier calculated ultrahigh acceleration was clarified [4] and the sophisticated Doppler-measurement was reproduced [5]. Measurements with 45 fs 5?1019 W/cm2 laser pulses [6] showed that 2.5 wavelength thick diamond layers did not show any tunnelling of light but high ion acceleration. After initial estimations, it will be reported how the dielectric swelling of the laser field is essential for the non-thermal direct nonlinear force plasma block acceleration as a collective interaction process. This is another example, how the collective interaction of solids with above petawatt sub-picosecond pulses is leading to conditions of macroscopic properties known from atomistic dimensions with excluding chaotic and delaying thermal processes known from longer laser pulse interaction.

[1] H. Hora, Nature 333, 337-338 (1988).

[2] H. Hora, Physics of Laser Driven Plasmas, New York: Wiley (1981)

[3] R. Sauerbrey, Phys. Plasmas 3, 4712-4716 (1996)

[4] H. Hora, J. Badziak et al. Phys. Plasmas 14, 072701/1-7 (2007)

[5] I. Földes, J.S. Bakos, Laser Phys. 10, 2640269 (2000)

[6] S. Steinke, A. Hening et al. Laser and Particle Beams 28, 215-221 (2010)

8780-88, Session 16

Generation of multi-GeV electron beam using PW laser system

Hyung Taek Kim, Ki H. Pae, H. J. Cha, I Jong Kim, Tae Jun Yu, S. K. Lee, Jae Hee Sung, Jungwon Yoon, Tae Moon Jeong, Jongmin Lee, Gwangju Institute of Science and Technology (Korea, Republic of)

Progress of femtosecond high-power laser system has reached peak power of petawatt and it provides new possibilities to enhance the performance of laser-wake field acceleration. Recently, a laser system with PW peak power has been developed at Advance Photonics Research Institute (APRI) and we applied this very intense laser pulses to electron beam acceleration. Here, we are presenting the multi-GeV electron beam generation using a PW-laser system by applying double-stage acceleration by two gas-jet media.

In the experiment, a laser pulse of 25-J energy was focused with a spherical mirror with focal length of 4 m and the focal spot size

was about 25 micron in full width half maximum (FWHM). The pulse duration was optimized by detuning the grating distance to produce positively chirped 60-fs pulse. We examine the electron beam generation with 4-mm and 10-mm supersonic He gas jet that produces energy of about 500 MeV and 1.1 GeV with gas density of 2.2x10^18 cm^-3 and 1.1x10^18 cm^-3, respectively. In order to increase electron energy further, we combine the two gas jets in serial to make longer gas medium. The backing pressures of two gas jets were controlled independently. We found that the electron energy can be much higher from the double-stage gas jet than those from single gas jets. We observed enhancement of electron energy up to very high energy range that is separated one peak at around 1.3 GeV and the other peak was about 3 GeV with the electron density of 1.9x10^18 cm^-3 for the first 4-mm gas jet and 5x10^17 cm^-3 for 10-mm jet. In addition, we examine the acceleration conditions from first stage to second stage with changing gas density of two gas jets and we found that the two acceleration regime in second stage; one is boosting electron energy by capturing electron bunches from first jet, and the other is elongation regime where the two gas jet has similar gas density. Consequently, this result of 3-GeV electron beam generation by double-stage gas medium using femtosecond PW laser system provides promising perspectives to high-energetic electron beam generation over 10-GeV energy using LWFA by applying multi-stage acceleration with multi-beam lines of PW laser systems.

8780-89, Session 16

Laser ion acceleration: from present to intensities achievable at ELI-Beamlines

Jirí Limpouch, Czech Technical Univ. in Prague (Czech Republic)

No Abstract Available

8780-75, Session PS

Energetic study of focused ultrashort Gaussian beams

Luis Carretero López, Pablo Acebal González, Salvador Blaya, Roque Fernando Madrigal, Antonio Fimia-Gil, Univ. Miguel Hernández de Elche (Spain)

It is well known that an ultrashort pulse consists of a coherent superposition of many frequency components. The propagation and diffraction of this kind of beams have been studied by many different authors. For example, Porras [1], using a method based on the analytical signal complex representation of polychromatic light, found a family of ultrashort pulsed light beams that solve the paraxial wave equation. Agrawal [2], using the angular spectrum representation, studied the propagation of ultrashort optical pulses inside a linear dispersive medium . Christov [3] also used the angular spectrum representation to analyze the evolution of the spatial and temporal characteristics of a short pulse propagating in vacuum. The effect of vectorial nature on spectral anomalies of ultrashort pulses passing through a rectangular aperture has been studied using the vectorial Rayleigh-Sommerfeld diffraction integrals [4]. Ultrashort laser pulse time evolution has been analyzed in reference [5] using Fresnel diffraction formula, showing that diffraction is not constant in time as the pulse travels through a circular aperture. Recently Banakh [6], using the angular spectrum approximation, analyzed the instantaneous intensity. As a result, it has been conjectured that in ultrashort focused Gaussian pulses the diffraction spreading of the focused beam decreases with the pulse duration, and for the limit case of a "delta-pulse", there is no diffraction. Rosanov [7] have noted that the introduction of the carrier frequency in the limit case of a "delta-pulse" loses its meaning. In fact, it is demonstrated that for "delta-pulses", almost of all of the nergy is contained in radiation with infinitely high frequencies, and as obvious consequence, there is not diffraction. In this paper we present an energetic study of focused ultrashort beams in the frequency domain using Fresnel integrals in order to study the diffraction spreading by analyzing the encircled energy at the focused plane. We have obtained the frequenecy wm which strongly contributes to the diffracted intensity as a function of carrier frequency and the pulse duration, showing that if this frequency is taken as reference instead of carrier frequency w0 there is always diffraction.

[1] Porras M A 1998 Phys. Rev. E 58 1086

[2] Agrawal G P 1999 Optics Communications 167 15

[3] Christov I 1985 Optics Communications 53 364

[4] Yang Y, Duan K, Jiang D, Zhang J and Chen Y 2010 Applied Physic B 98 125

[5] Lefrancois M and Pereira S 2003 Optics Express 11 1114

[6] Banakh V A 2011 Optics Letters 36 4539

[7] Rosanov N and Sochilin G 2012 Opti. Spect. 113 99

8780-90, Session PS

A LIF scheme for HIPER application based on the combination of ultrahigh laser nonlinear force driven plasma blocks and the relativistic acceleration of ions blocks

Stavros Moustaizis, Technical Univ. of Crete (Greece); Paraskevas Lalousis, Foundation for Research and Technology-Hellas (Greece); Heinrich Hora, The Univ. of New South Wales (Australia)

New numerical calculations based on a genuine two-fluid hydrodynamic model allow the study of the plasma block acceleration of solid fusion targets interacting with a high contrast ps-PW laser beam. Following previous theoretical developments [1, 2, 3, 4] on the nonlinear (ponderomotive) force the numerical results show an acceleration of 10^22 cm/s^2, which has been verified experimentally [5, 6]. This acceleration is few orders of magnitude higher than from thermal process and permit the plasma blocks to ignite and propagate a fusion flame in the solid target. For ps laser pulses with intensities up to 10^21 W/cm^2 interacting with thin targets the model shows that the relativistic acceleration of the electron cloud enables high currents of deuterium and He3 beams accelerating up to 80 MeV and 240 MeV respectively. The combination of the plasma block acceleration with the D [or He3] beams produced by ps-PW high contrast laser beams permit the increases of the fusion gain in the compressed target due to the complementary fusion energy of the nuclear reactions of particle beams with the target. Until now the fast ignition scheme is based on the energy deposition of the particle beam in the fusion target. In our new proposed fast ignition fusion scheme the main contribution of the particle beam is due to the nuclear fusion reactions produced in the compressed target by the D (or He3) beam or igniting the proton reaction with B11 (HB11) [7]. The proposed scheme simplifies the target compression configuration and improves the output produced energy especially for LIF projects with rep. rate up to 10 Hz like HIPER and LIFE.

[1] H. Hora, J. Badziak, et al., Fast ignition by laser driven beams of very high intensity, Physics of Plasmas 14 072701/1-7 (2007).

[2] P. Lalousis and H. Hora, First direct electron and ion fluid computation of high electrostatic fields in dense inhomogeneous plasmas with subsequent nonlinear laser interaction, Laser and Particle Beams 1, 283-304 (1983); H. Hora, P. Lalousis and S. Eliezer, Analysis of the Inverted Double Layers in Nonlinear Force Produced Cavitons at Laser-Plasma Interaction, Phys. Rev. Letters 53, 1650-1652 (1984).

[3] P. Lalousis, I. Földes & H. Hora. Laser and Particle Beams 30, 233-242 (2012).

[4] S. Eliezer. Laser and Particle Beams 30, 225-232 (2012).

[5] R. Sauerbrey, Acceleration of femtosecond laser produced plasmas, Physics of Plasmas 3, 4712-4716 (1996) .

[6] I. B. Földes, J. S. Bakos, K. Gal, S. Szatmari et al. Laser Physics 10 264-270 (2000)

[7] H. Hora & G.H. Miley, J. Energy and Power Engineering 5, 718-729 (2011).

Conference 8781: Integrated Optics: Physics and Simulations

Wednesday - Thursday 17–18 April 2013

Part of Proceedings of SPIE Vol. 8781 Integrated Optics: Physics and Simulations

8781-1, Session 1

Integrated design for integrated photonics: from the physical to the circuit level and back *(Invited Paper)*

Wim Bogaerts, Martin Fiers, Antonio Ribeiro, Univ. Gent (Belgium)

Silicon photonics offers the potential to make large-scale integrated photonic circuits with a complexity that has not been possible before. Photonic design tools cannot handle this well, and electronic design tools struggle with many photonic concepts. For example, photonic signals cannot be mapped easily into electrical voltage and currents, and much more information needs to be conveyed (a photonic signal for a C-band spectrum can easily require 1000 numbers per time step).

Silicon photonics is still very much designed at a physical level, also because fabrication tolerances are so tight, and full electromagnetic simulation is often needed. In addition, other physical effects (such as temperature) play an important role. These physical models should then be translated into a circuit model, which can be handled by a photonic circuit simulator. Taking all the physical effects from the electromagnetic simulation to the circuit level is not straightforward, because these different simulations are also executed in different tools, and component information needs complex translation or redefinition to work in different tools.

We have built an integrated design and simulation framework for photonics. IPKISS allows the designer to define the component once, and then use this same component at different levels of the design and simulation flow. A component can be defined as a layout mask for fabrication, but from that an electromagnetic modeling volume can be derived for eigenmode solving or FDTD simulation. Our framework interfaces with MEEP, but the standard Python language makes it easy to integrate other simulators as well. Simulation results from MEEP can be used to define scatter matrix, that can then be used in a circuit simulator. Again, different tools can be use; we use our in-house tool Caphe. The transition from the physical to the circuit level requires no redefinition of the component. By changing a parameter of the component we can run through this simulation flow again. The layout of the component or circuit can also be exported to GDSII file for direct fabrication, and we can even incorporate the measurement and test routines for later characterization.

This design flow has been validated on tens of fabrication runs, making complex components such as arrayed waveguide gratings with good precision: for such devices, components can be broken down in a smart way, where each part uses the best suited simulation technique: FDTS, mode solving, analytical model,…

The framework has also been interfaced, as a proof of concept, with the Cadence design environment, illustrating that photonic design tools can be coupled to standard electronic design automation software.

8781-2, Session 1

Analysis of parasitic effects in PICs using circuit simulation

Emil Kleijn, Meint K. Smit, Xaveer J. M. Leijtens, Technische Univ. Eindhoven (Netherlands)

An understanding of parasitic effects is essential to maximize the performance of a Photonic Integrated Circuit (PIC). Using our circuit simulator, we are able to model mode conversion at the interface between straight and bent waveguides, parasitic reflections in multi-mode interference couplers (MMIs), interference between multiple modes, residual facet reflections, and reflections at junctions between components. Even though these effects are usually low in intensity, around -20dB to -30dB from the main signal level, they can still have a strong influence on the circuit performance. This is because the mentioned parasitic effects are coherent with the desired signal and interference between them is therefore a field effect. By analyzing three different circuits, and comparing the results to measurements, we show that these effects need to be carefully managed in order to ensure circuit performance. The circuits we investigate are a Fabry-Perot cavity, a Mach-Zehnder interferometric structure, and a Michelson interferometer. Especially residual reflections coming from angled facets and back-reflections in MMIs are shown to be the main parasitic effect in the investigated circuits.

We use a linear scatter-matrix approach to simulate optical circuits. We adapted an existing s-matrix program from Agilent, Advanced Design System (ADS), that was developed for radio frequency applications. Optical circuits can be simulated using this simulator by adding models that describe individual components. We have added such models for straight waveguides, curved waveguides, tapers, MMIs, multi-mode interference reflectors (MIRs), arrayed waveguide gratings etc. Most of the models apply Eigen Mode Expansion (EME) using only the guided modes. Next to these we employ a number of advanced analytical models. One of those describes mode coupling in parabolic tapers, and another gives an estimate of reflections occurring at junctions in MMIs.

The circuits we investigate were designed for an indium phosphide based generic integration technology. Through the European PARADIGM project we obtained access to this platform. The platform offers, among other functionality, optical amplifiers, phase modulators based upon the electro-optic effect, detectors and passive waveguiding structures. The layer stack for the modulators and passive waveguides consists of a multiple quantum well core on a n-doped substrate with a p-doped top cladding. Waveguides are defined by deep-etching and air is used as a lateral cladding. The high lateral index contrast allows for tight bends of 100 um bending radius. However, parasitic reflections can be strong due to this high index contrast. The designed circuits are all built up from linear building blocks. This allows them to be analyzed very accurately by the linear s-matrix simulator. We demonstrate an excellent match between simulation results and measurement results. Using our approach, designers can better judge the impact of parasitic effects on their circuit design. This allows them to change their design in order to increase performance.

8781-3, Session 1

Thermo-optic simulations of silicon nitride / polymer hybrid waveguides

Anjin Liu, Fraunhofer HHI (Germany); Ziyang Zhang, Dongliang Liu, Norbert Keil, Norbert Grote, Fraunhofer-Institut für Nachrichtentechnik Heinrich-Hertz-Institut (Germany)

Abstract

Polymer materials are known to possess relatively high thermo-optic effects and at the same time low thermal conductivity [1], which makes it ideal to realize thermally tunable devices such as variable optical attenuators [2], digital optical switches [3], tunable fiters [4], and so on. The thermo-optic coefficient (TOC) of polymer materials is on the order of -1.0?10-4/C°. The negative sign of the TOC is different from other inorganic optical materials such as silicon and glass. This characteristic has been explored in making temperature-insensitive optical devices [5].

Recently we have developed a technology to deposit highly transparent silicon nitride (SiNx) material directly on polymer to create SiNx waveguides completely buried in polymer cladding. Instead of pursuing an athermal solution, we have designed the waveguide so that the majority of the mode spreads into the polymer cladding, where the negative TOC dominates. In this way, thermally tunable devices can be made similar to the all-polymer situation but with the advantage that the high index contrast with silicon nitride can make the device much more compact. In addition, only one polymer material is needed, allowing the freedom to choose materials with large TOCs yet not being confined with the burden of creating another polymer material with similar TOC but different refractive index for the waveguide.

In this work, we study different SiNx waveguide geometries and compare their mode confinement factors. Optimal taper dimension for coupling with fibers and laser diodes are also investigated. Thermal simulation (Thermo-optic solver, Fimmwave) is carried out to find the

optimal heating electrode configuration. Additional features such as air trenches are designed to isolate the heat dissipation in order to improve the heating efficiency.

References

[1] H. Ma, "Polymer-based optical waveguides: Materials, Processing, and Devices", Adv. Mater. 14, (19), pp 1339-1365 (2002).

[2] U. Siebel, "Polymer digital optical switch with an integrated attenuator", Photonics Technology Letters, 13, (9), pp. 957 - 959 (2001).

[3] Sang-Shin Lee, "Variable Optical Attenuator Based on a Cutoff Modulator with Tapered Waveguides in Polymers", Journal of Lightwave Technology, 17, (12), pp. 2556 (1999).

[4] D. de Felipe, "Widely-Tunable Polymer Waveguide Grating Laser," 16th European Conference on Integrated Optics (ECIO) 2012, paper TuPWGL.

[5] N. Keil, "Athermal polarisation-independent arrayed- waveguide grating (AWG) multiplexer using an all polymer approach", J. Appl. Phys. B, Lasers Opt., 73, (56), pp 619–622 (2001).

8781-4, Session 1

Numerical simulation of multi-splitting widely tunable filter on SOI

Andrey Tsarev, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation)

Paper present results of numerical investigation of new tunable optical filter which utilized multiple coupled silicon wire waveguides on SOI structures. Filter is analyzed by finite difference time domain (FDTD) method. Unfortunately, complicated three dimensional (3d) optical structures are impossible to study by 3d FDTF due to unrealistic demand on computer recourses. Such structures are often analyzed by 2d FDTD which is typically combined with effective index method (EIM). The last one has the principal limitation which comes from the fact that real 3d waveguide with 2 different cross dimensions (h and W) is examined by 2d waveguide with the only one size parameter (W). Thus wavelength dependence of mode effective index in 3d and 2d waveguides have to be principally different which results in the great error in studding impulse excitation of these devices by 2d FDTD method due to wrong group index Ng determined by EIM. In order to improve simulation accuracy we introduce modified effective index method (MEIM) which correctly describes in 2d case both the phase and the group indexes in 3d strip waveguide, typically used in silicon photonics in thin silicon-on-insulator (SOI) structures. MEIM utilizes the combined index profile containing the two spatial parameters as in actual 3d waveguide. Namely, the central part with refractive index NSi has the width w (nearly to waveguide height h) and it is mainly responsible for the group index Ng. The base part has the same width W as in 3d waveguide and refractive index Nb which is mainly responsible for the phase index value Np. By variation of w and Nb it is possible to fit in a wide wavelength range the effective index of combined 2d waveguide to the mode index of 3d waveguide. As a result, this combined structure provides much better agreement of the group and the phase velocities in both 2d and 3d waveguides and thus it inherently provides the better accuracy than EIM in studding optical devices in frequency domain.

Particularly, for the novel tunable optical filter which utilizes multiple coupled silicon wires, the free spectral range (FSR) determined by EIM differ from 3d case by about 30% instead of typical error about 1%-2% (dependent on the tuning range) which is provided by MEIM. Thus our results obtained jointly by 2d FDTD and MEIM correctly describe real 3d structures and could be regarded as numerical experiments. Numerical simulation of novel filter proves its general conception and demonstrates that a short 360 mkm structure with 32 couplers has spectral resolutions 1.5 nm, loss -1 dB and sidelobes below -26 dB. It provides wavelength tuning (without Vernier principle) within total FSR 36 nm at central optical wavelength 1.55 mkm by temperature change up to 100 C in four sets of thermo optic phase shifters. Device of 1 cm size provides 0.05 nm filter linewidth. Filter can be manufactured by CMOS compatible technology and very promising for applications in photonics.

8781-36, Session 1

Advances in integrated quantum photonics *(Invited Paper)*

Damien Bonneau, Josh W. Silverstone, Pete Shadbolt, Alberto Peruzzo, Jonathan C. Matthews, Jeremy L. O'Brien, Mark G. Thompson, Univ. of Bristol (United Kingdom)

Quantum information technologies offer a new and powerful approach to processing and communicating information. By harnessing the quantum mechanical properties of single particles of light, quantum photonic technologies aim to realise new advancements in communications, sensing, simulation and computation. Quantum information processing promises huge computation power, whilst quantum communications offers the ultimate in information security - guaranteed by the laws of physics. Until recently, optical implementations of quantum architectures have been realised using large-scale (bulk) optical elements, bolted onto optical tables. This approach has lead to severe limitations in the miniaturization, scalability, stability and performance of such systems. In this talk I will present an integrated quantum micro-chip architecture that overcomes this bottleneck to enable integrated photonic quantum circuits for high performance, miniaturization and scalability.

I will describe recent developments, including the high fidelity operation of key quantum photonics components, such as on-chip two-photon quantum interference and controlled-NOT logic operations. Other advancements include dynamically reconfigurable circuits for on-chip entanglement generation and manipulation, a small-scale quantum factoring algorithm and the quantum simulation of bosonic, fermonic and anyonic multi-particle quantum walks. I will describe our latest results on the development of a silicon-based quantum photonics technology platform, where we are able to generate and manipulate quantum states of light in waveguide circuits thousands of times smaller than previous demonstrations. These results represent key steps that are crucial for the development of practical quantum photonic technologies for applications in quantum communication, metrology, simulation, computation and fundamental science.

8781-5, Session 2

Silicon integrated optoelectronics *(Invited Paper)*

Michael Hochberg, Univ. of Delaware (United States)

Silicon Integrated Optoelectronics

CMOS-compatible silicon is not an obvious material system for building high-performance optical devices. But, over the last ten years, it has become possible to build fairly complex integrated optical systems at telecommunications wavelengths on electronics-compatible silicon substrates. In fact the complexity of these systems has been approximately doubling every year, and this trend is projected to continue for at least the next several years.

With a combination of CMOS electronics and photonics in the same chip, we can gain control of both photons and electrons, while preserving the powerful economics of the VLSI revolution.

The focus of this talk will be on the OPSIS project, which is a new initiative aimed at creating an open infrastructure for building fully integrated optoelectronic devices in silicon, and on some of the new science and engineering that are enabled by these devices.

8781-6, Session 2

Fourier-transform spectrometer chip with silicon spiral waveguides

Pavel Cheben, National Research Council Canada (Canada); Aitor V. Velasco, Univ. Complutense de Madrid (Spain); Przemek J. Bock, Jens Schmid, Jean Lapointe, André Delâge, Siegfried Janz, National Research Council Canada (Canada); Maria L. Calvo, Univ. Complutense de Madrid (Spain); Dan-Xia Xu, National Research Council Canada (Canada); Mirek

Florjanczyk, York Univ. (Canada)

Compact spectral filters with a small footprint are required for a wide range of applications, including wavelength division multiplexed communications, optical interconnects, biological and environmental sensing, and space instrumentation. Planar waveguide devices such as arrayed waveguide gratings (AWG), echelle gratings, lattice filters, ring resonators and sidewall grating filters can achieve a high spectral resolution for a small device footprint, but their optical throughput (étendue) is largely limited by the requirement of a single mode input waveguide. Étendue is of critical importance for spectroscopy applications, especially when spatially extended and incoherent sources are analyzed. This limitation can be overcome with planar waveguide Fourier-transform (FT) spectrometers based on the principle of spatial heterodyne spectroscopy (SHS). Here we report a stationary Fourier-transform spectrometer chip implemented in silicon microphotonic waveguides. The device comprises an array of 32 Mach-Zehnder interferometers (MZI) with linearly increasing optical path delays between the MZI arms across the array. The optical delays are achieved by using silicon wire waveguides arranged in tightly coiled spirals with a compact device footprint of 12 mm2. Spectral retrieval is demonstrated in a single measurement of the stationary spatial interferogram formed at the output waveguides of the array, with a wavelength resolution of 40 pm within a free spectral range of 0.75 nm. The phase and amplitude errors arising from fabrication imperfections are compensated using a transformation matrix spectral retrieval algorithm.

8781-7, Session 2

A general approach for robust integrated polarization rotators

Carlos A. Alonso Ramos, Robert Halir, Alejandro Ortega-Moñux, Univ. de Málaga (Spain); Pavel Cheben, National Research Council Canada (Canada); Laurent Vivien, Institut d'Électronique Fondamentale (France); Iñigo Molina-Fernández, Univ. de Málaga (Spain); Delphine Marris-Morini, Institut d'Électronique Fondamentale (France); Sigfried Janz, Dan-Xia Xu, Jens Schmid, National Research Council Canada (Canada)

The high refractive index contrast of the SOI and indium phosphide platforms makes propagation characteristics for the TE- and TM-like modes largely disparate. To mimic polarization independent operation, polarization diversity schemes are typically used with the polarization splitters and rotators as the key components.

Recently, several solutions have been proposed to implement integrated polarization rotators for these high index contrast platforms, including designs based on asymmetric waveguides with two etch depths [1], waveguides with sloped sidewalls [2], and waveguides with a single or multiple trenches [3]. In order to achieve the required conversion efficiency both, specific tilt of the hybrid modes (45°) and rotator optical path length need to be implemented accurately. However, both values are very sensitive to waveguide geometry variations, thus even small fabrication errors substantially reduce conversion efficiency [4].

In this work we propose a scheme that drastically reduces the sensitivity of waveguide polarization rotators to fabrication variations. The device is implemented using a rotator waveguide split in three sections joined by two polarization phase shifters.

In a conventional rotator the hybrid modes must be tilted at exactly 45°, and the rotator length has to match their half beat length. With our approach it can be analytically shown that by adjusting the polarization phase shifters, perfect polarization rotation is achieved for mode tilts in the waveguide rotators between 15° and 75° and a wide range of rotator lengths [5]. This significantly relaxes the fabrication tolerances for the waveguide rotator. The polarization phase shifters can be realized using thermo-optical or electro-optical effects.

Simulation results for a polarization rotator waveguide with a 30° error in mode tilt angle at a wavelength of 1.55µm show a 4 dB extinction ration for the conventional approach and 40 dB extinction ratio when the same rotator waveguide is used in the proposed configuration. A remarkable (35 dB) improvement in extinction ratio is achieved. Similar extinction ratios are achieved for the complete C-band (1.52-1.58 µm).

[1] C. Alonso-Ramos et al., "Polarization rotator for InP rib waveguide," Opt. Lett. 37, 335-337, 2012.

[2] H. Deng et al., "Design rules for slante-angle polarization rotators," J. Lightwave Technol. 23, 432-445, 2005.

[3] A. Velasco et al., "Ultracompact polarization converter with dual subwavelength trench built in a silicon-on-insulator waveguide," Opt. Lett. 37, 365-367, 2012.

[4] H. Deng et al., "Fabrication tolerance analysis of asymmetric silicon-on-insulator polarization rotators," J. Opt. Soc. Am. A 23, 1741-1745, 2006.

[5] C. Alonso-Ramos et al., "Highly tolerant tunable waveguide polarization rotator scheme," Opt. Lett. 37, 3534-3536, 2012.

8781-8, Session 2

Design and analysis of ultra-small radius microring resonator

Cheng Yu Wang, National Sun Yat-Sen Univ. (Taiwan); Chih Wei Tseng, National Tsing Hua Univ. (Taiwan); Yung Jui Chen, National Sun Yat-Sen Univ. (Taiwan)

Silicon photonics is becoming a well developed technology for integrated optics. One of the advantages of SOI devices is its tightly confined mode, which allows low-loss sharply bended waveguide. One can fabricate small radius micro-ring devices that yield large free spectral range (FSR). Thus, silicon photonics can be a key platform for large scale optical communication and data communication planar lightwave circuits (PLC). Various functional devices based on these characteristics have been realized, such as optical switch, optical filter/add-drop multiplexer, interleaver, and so on.

High performance micro-ring based PLCs require precise control of the (waveguide-ring, ring-ring) coupling coefficients and low ring propagation loss. Recently we have shown experimentally that for small radius ring resonators, when the coupling gap is small (to achieve large coupling coefficient), there is a large increase of ring propagation loss due to coupling to radiation modes at the coupling region [1]. This phenomenon greatly reduces the flexibility of designing ring based PLCs. In this paper, we present a detailed analysis of a novel conformal race-track micro-ring resonator to circumvent this serious problem.

A traditional race-track ring resonator structure, of which two straight waveguides are embedded in a ring to increase the interaction length with the bus waveguide, is utilized to enhance the coupling coefficient [2]. However, its FSR becomes smaller as the optical path of the ring increases. Here we introduce a novel structure of which the bus waveguide is bent conformally with respect to (parallel with) the ring waveguide, we termed it the conformal race-track design. As a result, the coupling coefficient can be raised without a drop in FSR.

The designed bus waveguide can be divided into two parts, within and outside the coupling region. Following coupled mode theory concept, the mode coupling between two waveguides is maximized when the two waveguides are phase matched. Therefore, we modify the structure of the bus waveguide within the coupling region to achieve the phase matching condition, i.e. shrink the width and change the height of the waveguide. Furthermore, the bus waveguides outside the coupling region are bent into two curves with their radii equal to that of the ring. Thereby, the whole bus waveguide is phase matched with the ring.

Owing to its conformal race-track configuration, a high coupling coefficient and large FSR can be obtained. Comparing to the general race-track ring resonator, this design stands out as a promising passive device which shows excellent applicability in optical communication and optical interconnection applications. The designs and performances of large FSR (greater than 4000 GHz) and narrow flat-top passband (25 GHz) micro-ring based filters will be presented.

[1] Chih-Wei Tseng et.al. ," Proceddings of the 2012 IEEE International Conference on Group IV Photonics, USA, August, 2012

[2] P. Dumon et.al. , "Low-loss SOI photonic wires and ring resonators fabricated with deep UV lithography," IEEE Photon. Technol. Lett. 16, 1328 (2004).

8781-9, Session 2

Analysis of couplers between photonic nanowires and subwavelength grating waveguides

Jirí Ctyroky, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Pavel Kwiecien, Ivan Richter, Czech Technical Univ. in Prague (Czech Republic); Pavel Cheben, National Research Council Canada (Canada)

As it has been shown recently, subwavelength grating (SWG) waveguides represent a promising solution how to add the variability of (effective) refractive index variation into the design of integrated-optical components and devices based on silicon-on-insulator (SOI) platform without significantly increasing fabrication complexity. An SWG waveguide is formed by a subwavelength (quasi)-periodic structure consisting of short nominally rectangular blocks of silicon of different dimensions embedded into a lower-index superstrate. As a result, to the first approximation, the SWG waveguide behaves as a channel waveguide with a refractive index that depends on the filling factor of silicon in the superstrate. By changing the filling factor, i.e., the duty-cycle of the SWG structure, its "equivalent" refractive index can be varied essentially between that of the superstrate and that of silicon.

Our contribution is devoted to a numerical analysis of light coupling between a conventional silicon nanowire waveguide and a periodic SWG waveguide by means of a tapered SWG coupler. The role of the coupler is to assure the smooth and low-loss transition from a "classical" mode of a photonic nanowire to a Bloch mode of a periodic SWG waveguide that propagates with a different group velocity. To increase the reliability of numerical simulations, two independent 3D numerical codes based on different formulations of a Fourier modal method (FMM) are used for the analysis. Results of modeling of several configurations of the taper SWG couplers will be presented and compared. Particular attention will be paid to the distribution of radiation losses along the coupler. Radiation losses of different configurations of SWG waveguides due to the finite thickness of the SOI bottom oxide (BOX) layer will also be investigated.

8781-10, Session 3

Self-tuned laser cavity: from a network-embedded configuration to silicon integration *(Invited Paper)*

Alban Le Liepvre, Romain Brenot, Alcatel-Thales III-V Lab. (France)

Wavelength selectable lasers can be realized by coupling a set of Reflective Semiconductor Amplifiers (RSOA) to an Arrayed Waveguide Grating (AWG) followed by a mirror to close the cavity. They can be deployed as a part of a distribution network, such as Wavelength Division Multiplexing Passive Optical Networks (WDM-PON), or as compact WDM transmitters. The unique advantage of these emitters is to operate without any Bragg grating, which facilitates their industrialization. However, they are very interesting research topics:

• In the network embedded configuration, the modulation period is much shorter (< 1 ns) than the photon's round-trip time (> 1 µs). Theoretically, fast modulation should not be possible. We will explain how the RSOA can enable this fast modulation.

• In the integrated device, the challenge is to achieve fast and single-mode operation. We will present some achievements.

Finally, we will summarize state-of-the-art performances in both configurations, and draw some conclusions on the role of photonic integration.

8781-11, Session 3

Simultaneous optimization of confinement and thermal performance for heteroepitaxial InP on SoI hybrid lasers

Cheng-Xin Pang, Mondher Besbes, Henri Benisty, Lab. Charles Fabry (France)

The hybrid evanescent lasers made from an active InP stack onto a patterned silicon-on-insulator (SoI) can be made substantially more effective using direct bonding, without any oxide or polymer layer between silicon and active stack. Then, it becomes interesting to form a lateral silicon pattern around the central ridge waveguide that combines the role of thermal sinking as well as the role of optical cladding. It leads to the possibility of implementing high index contrast gratings (air/silicon) embedded in the laser or amplifier, or simply, as here, effective media.

However, the two functions (thermal and optical) are contradictory, more silicon in the cladding being sought for thermal purpose, and more air for the optical confinement purpose. Thus, different shapes of silicon patterns can lead to different compromises. In this framework, we first study thin one-dimensional air slots that are viewed as an effective medium, etched through the upper part of the silicon slab. Given the TE-like field polarization, the effective index seen is very different for slots parallel or perpendicular to the field (and thus perpendicular or parallel to the ridge), with an advantage for the slots parallel to the ridge, whose effective average index is low even for a fraction of air as small as f=0.127.

We next consider a 2D array of holes, since their average index can be low without demanding too small feature sizes or too large aspect ratio. We find that realistic compromises are most feasible with this approach, typically with periods around 200 nm, diameter of 80nm, depth of 300 nm and a square lattice.

Finally, we apply Southwell's popular flip-flop algorithm to optimize the design based on air slots, considering sequence made of thin slices that can be either silicon or air. We use an ad hoc thermal figure of merit and require the mode to remain close to the point of equal confinement between silicon and active region. The converged optimal sequence reveals that only two to three slots may suffice, but not trivially arranged, the closer to the central ridge being larger than further ones, and silicon only being adequate in the outer area.

More discussions on the design of transitions area at the ends of active structures, whereby the mode needs to "go up" or "go down", will be provided.

The application of the flip-flop algorithm is novel in the context of integrated optics and effective medium. The unique possibility to carve the underlying silicon provides novel avenues and calls for the full exploration of the opportunities of this system of clear industrial interest.

Further work in the frame of the COHEDIO French ANR collaboration with LPN laboratory and 3-5 Lab will lead to implementation of these designs.

8781-12, Session 3

Modelling and characterization of heteroepitaxially bonded InP-based structured on SoI for hybrid lasers

Cheng-Xin Pang, Mondher Besbes, Lab. Charles Fabry (France); Anne Talneau, Ahmad Itawi, Lab. de Photonique et de Nanostructures (France); Guang-Hua Duan, Alain Accard, Francois Lelarge, Alcatel-Thales III-V Lab. (France); Henri Benisty, Lab. Charles Fabry (France)

We investigate the guiding properties of directly bonded hybrid silicon/active InP structures made by direct hetero-epitaxial bonding between the patterned silicon of the SoI wafer and an InP cap layer of an active 1550 nm stack.

We will first briefly update the recent results on such directly bonded devices as regards material characterization, notably properties obtained by TEM microscopy and by photoluminescence mapping. We

will then detail what are the strategies to implement a nanostructured silicon cladding that combines good optical confinement through a low effective-medium index and as much thermal conduction as possible (hence as much silicon vertical bridges as possible). This nanostructuring can be 1D or 2D. Thus, we will give the advantages of specific 1D and 2D patterns based on the physical field profiles of interest, and discuss the results of “flip-flop” optimization.

We will next describe results that are obtained currently through photoluminescence mapping of directly bonded structures that comprise silicon waveguides with cladding inspired by the modeling describe above. The data first help to quantify the evolution of confinement factor, as a function of the silicon cladding's nanostructures parameters, such as the period, the duty cycle or the aspect ratio. They should also help assessing the thermal performance, using the transient response in pulsed regime. We eventually discuss how these tests of novel opportunities for the guiding schemes, opened by the direct bonding approach, also provide effective designs to be implemented in lasers, amplifiers, or in their associated taper/access structures.

8781-13, Session 3

Dual-wavelength operation of monolithically integrated arrayed waveguide grating lasers for optical heterodyning

Robinson C. Guzman, Alvaro Jimenez, Univ. Carlos III de Madrid (Spain); Katarzyna Lawniczuk, Technical Univ. of Eindhoven (Netherlands) and Warsaw Univ. of Technology (Poland); Antonio Corradi, Xaveer J. M. Leijtens, Erwin A. J. M. Bente, Technische Univ. Eindhoven (Netherlands); Guillermo Carpintero, Univ. Carlos III de Madrid (Spain)

A cost-effective solution to provide higher data rates in wireless communication systems is to push carrier wave frequencies into the millimeter wave (MMW) range. Currently, regulatory bodies around the world are allocating frequency bands within the E-band (71-76GHz, 81-86GHz) and F-band (92-96GHz). Photonics is a key technology to generate low phase noise signals in these bands, offering different methods of generating continuous MMW with varying performance in terms of frequency bandwidth, tunability, and stability.

Optical heterodyning is one such method, requiring two optical wavelengths spaced by the frequency that we aim to generate. The simplest approach is to use two distributed feedback lasers, which unless a phase locking technique is employed, has poor spectral purity since the noise from the two sources is uncorrelated. One common method is to use a narrow linewidth single-mode continuous-wave (CW) laser with external modulation to generate an optical double-sideband signal with suppressed carrier (DSB-SC). Integrating on a Planar Lightwave Circuit (PLC) an arrayed-waveguide grating (AWG) to select the modes for heterodyning and a Y-junction combiner, it was demonstrated that a 120 GHz signal could be generated with a phase noise better than ?75 and ?85 dBc/Hz at offset frequencies of 100 Hz and 1 kHz respectively. Thus, photonic integration can thus become a key factor, not just in reducing system complexity and cost, but also in improving the performance.

Recently, we demonstrated for the first time to our knowledge the generation of a 95-GHz signal using a monolithically integrated arrayed waveguide grating multi-wavelength laser (AWGL). The devices were fabricated in an indium phosphide (InP) based platform within a multi-project wafer run using active-passive integration. The device uses an arrayed-waveguide grating (AWG) as intra-cavity filter, with up to 16-channel sources with independent amplifiers and a booster amplifier on the common waveguide. The AWG was designed for a central wavelength ?c = 1551 nm with a channel spacing ?? = 100 GHz (0.8 nm) and a free spectral range (FSR) of 900 GHz (7.2 nm).

The laser cavity is formed between cleaved facets of the chip, and the two wavelengths required for optical heterodyning are generated from two channels of the AWG, which are activated simultaneously biasing their corresponding SOA. In this work, we analyze the effect of the Boost SOA, which is shared by the two wavelengths, on the dual wavelength operation . We map the optical spectrum sweeping the two channel and Boost bias currents, which show the interaction among the different SOAs, and reveal the current levels which offer a dual wavelength operation of the device. The size of dual wavelength operation region depends greatly on the Boost SOA bias level, in which high currents are desirable to increase the optical output power while we avoid that this SOA gives rise to optical modes that are not channel modes. Initial results of a numerical model of the AWGL will also be presented, in which a digital filter is used to implement the AWG frequency behavior.

8781-14, Session 3

Chirp reduction and on/off contrast enhancement via optical injection locking and coherent carrier manipulation

Radan Slavik, Univ. of Southampton (United Kingdom); Joseph Kakande, Alcatel-Lucent Bell Labs. (United States); Richard Phelan, John O'Carroll, Brian Kelly, Eblana Photonics Ltd. (Ireland); David J. Richardson, Optoelectronics Research Ctr. (United Kingdom)

The most cost-effective solution for modulating data on an optical carrier is via direct modulation of a semiconductor laser. Unfortunately, this technique suffers from high chirp that can be somewhat reduced by limiting the on/off modulation ratio i.e. by keeping the signalling laser well above its threshold when transmitting both, logical '0' and '1'. There are several techniques for further suppressing this chirp, generally based on self-injection, or optical injection locking of the directly-modulated laser (slave) to another laser (master) that emits cw light. This technique is very efficient when the slave laser is operated well above threshold but, similarly to the directly-modulated free-running laser, has its limits when the slave laser is operated close or even below its threshold during transmission of the '0' level. Thus, this technique does not allow for an improvement in the on/off modulation ratio, although it strongly reduces the chirp.

We propose a transmitter that addresses both issues – chirp and the limited on/off contrast. We achieve it by a minor modification in the structure of the optical injection-locked-based transmitter described above. We exploit the mutual coherence between the slave and the master lasers, which allows for coherent addition or subtraction of a portion of the carrier signal from the directly-modulated laser. The amplitude-modulated signal with limited on/off contrast can be viewed as the superposition of a signal with ideal on/off contrast and a 'cw offset'. This 'cw offset' is in fact an unmodulated carrier. It can be removed by interfering it destructively with a component of the master signal which, due to optical injection locking, is coherent with the carrier of the slave laser. Practically, we combine the output of the directly-modulated laser with a portion of the cw master and set the phase between them to obtain destructive interference. This results in removal of the 'cw offset' and thus allow for obtaining high on/off contrast signal. Experiments are carried out at 10 Gbit/s and beyond. In the future, this proof-of-principle demonstration of the transmitter, consisting of two lasers, one 2x2 coupler and a mirror, could be integrated to provide a robust and low-cost solution.

8781-15, Session 4

Efficient wavelength conversion in integrated structures: novel applications *(Invited Paper)*

Roberto Morandotti, Marco Peccianti, Alessia Pasquazi, Matteo Clerici, Lucia Caspani, Chris Reimer, Institut National de la Recherche Scientifique (Canada); Sai-Tak Chu, Brent E. Little, Infinera Corp. (United States); David J. Moss, The Univ. of Sydney (Australia)

We summarize our recent results on the generation and the detection of ultrafast optical signals in CMOS-compatible monolithic devices by exploiting the third order nonlinearity of glass based waveguides. For example, schemes based on Four Wave Mixing (FWM) have the advantage of being suitable for centro-symmetric materials, such as silicon or glass – both being fundamental platforms for integrated optics, and compatible with the current CMOS technology. In our talk, we will discuss our recent results, achieved in high index glasses, corresponding to the above-mentioned requirements. We show that

novel optical circuits based on the use of high quality ring resonators can be used to realize stand alone and self-pumped OPOs, to generate stable trains of pulses at 200 GHz rep rates with a novel passive mode-locking scheme (that could be efficiently used in certain metrology applications such as the generation of dual combs) and perhaps even to realize efficient schemes for the generation of correlated photons pairs. Furthermore, if time allows, we will present a device based on a spiral waveguide for the amplitude and phase characterization of ultrafast optical pulses working up to 1 THz bandwidth and 100ps time-duration, together with a new phase-recovery algorithm.

8781-16, Session 4

Nonlinear interactions of a supercontinuum and a weak laser to measure high order dispersion *(Invited Paper)*

Juan A. Castañeda, Univ. Estadual de Campinas (Brazil); Andrés Gil-Molina, Univ. de Antioquia (Colombia); Ana M. Cardenas, Univ. of Antioquia (Colombia); Hugo L. Fragnito, Univ. Estadual de Campinas (Brazil)

We analyze the interaction of a strong broadband source, such as a supercontinuum or spontaneous emission noise, with a weak narrow-line laser in a nonlinear and dispersive single mode optical waveguide. We present a theory for a generic waveguide, and experimental validations using optical fibers. Under quite general conditions, a narrow peak is observed in the spectrum at the output of the waveguide. This arises from the fact that for any Fourier component of the broadband source, another component exists such that when combined with the laser, a perfectly phase matched four wave mixing (FWM) peak is generated. It is remarkable that all these FWM processes produce a phase matched tone at exactly the same frequency. Because the peak position depends critically on the high order chromatic dispersion parameters of the waveguide, this effect can be used to measure dispersion and dispersion fluctuations. By using short pulses we demonstrate the measurement of the high order dispersion map of optical fibers. We show also that it is possible to infer, from this type of interactions, the magnitude of the variations of the waveguide core dimensions.

8781-17, Session 4

Selective amplification of frequency comb modes via optical injection locking of a semiconductor laser: influence of adjacent unlocked comb modes

David S. Wu, David J. Richardson, Radan Slavik, Optoelectronics Research Ctr. (United Kingdom)

Optical frequency combs (OFCs) are commonly used in the field of metrology and spectroscopy because of their ability to measure arbitrary optical frequencies with very high accuracy. OFCs also have applications in various other fields such as arbitrary waveform generation, terahertz generation and telecommunication. Many of these applications do not require the entire OFC spectrum and may only require a few comb modes which can be extracted through a series of filtering and amplification steps. Optical injection locking of a semiconductor laser is a technique which can selectively amplify individual comb modes - simultaneously combining the filtering and amplification processes. This is achieved by limiting the size of the locking bandwidth of the slave laser such that it contains only a single comb mode.

We have previously characterised the long-term and short-term locking stability of a semiconductor laser injection locked to an individual OFC mode. While performing this characterisation, we observed that adjacent comb modes to the one being locked were also being slightly amplified by the injection locking process. This was despite these modes being outside the locking bandwidth. These amplified sidemodes behave as unwanted noise and were found to degrade the quality of the locking process. It was also observed that the amount of amplification of these unwanted sidemodes was dependent on two factors: the frequency detuning between the slave laser and the comb mode it was locked to, and the optical power injected into the slave laser.

In this work, we will further study this sidemode amplification. In particular, we will be looking at the mechanism behind this sidemode amplification inside the semiconductor laser and characterise the relationship between frequency detuning and injection power with the amount of sidemode amplification. We believe a better understanding will allow us to maximise the suppression of this effect and to improve the quality of the optically injection-locked laser output.

8781-18, Session 4

Enchancemnt of the optical power stimulated by impact ionization in GaSb-based heterostructures

with deep quantum wells

Maya P. Mikhailova, Geogry G. Zegrya, Leonid V. Danilov, Eduard V. Ivanov, Karina V. Kalinina, Nikolay D. Stoyanov, Yuri P. Yakovlev, Ioffe Physico-Technical Institute (Russian Federation); Eduard Hulicius, Alice Hospodkova, Jiri Pangrac, Maria Zikova, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Hafiz M Salikhov, Ioffe Physico-Technical Institute (Russian Federation)

We report demobstration of superlinear electroluminescence and enhancement of the optical power in GaSb-based nanoheterostructures with deep narrow Al(As)Sb/InAs0.84Sb0.16/Al(As)Sb quantum wells (QW) grown by metal organic vapour phase epitaxy (MOVPE). The structures under study were grown on n-GaSb:Te substrates at low pressure in AXTRON-200 machine and consisted of 20 nm AL(As)Sb/5 nm InAs0.84Sb0.16/20 nm Al(As)Sb layers and capping by 0.5 µm p-GaSb layer. Samples were prepared as mesa-diodes by standars photolithography. Theoretical calculation of the energy spectrum of the carriers in the QW was done according to the four-band Kane model.

Electrolumenescence spectra were measured in dependence of drive current (0-250 mA) in the range of the photon energy 0.6-0.8 eV at 77 K and 300 K. Intensity of EL spectra and optical power increased with drive current and it can be approximated as P=A?IB, where A is fitting parameter, I is drive current and B is index of the power. It was found as B=1.93 and 3 at 77 K and 300 K, respectively.

We explain the obtained results by contribution into radiative recombination of additional electron-hole pairs which were produced during process of impact ionization by hot electrons heated by passing high band offset ∆EC=1.27 eV at the heterointerface between AlAs layer and the first electron level Ee1 in a well.

Theoretical evaluation of the impact ionization process in QW structure and several cases of the impact ionization in dependence on QW width were done.

8781-37, Session PS

Almost lossless multiple crossing of silicon wires by means of vertical coupling with a polymer strip waveguide

Andrey Tsarev, Eugeny Kolosovsky, A.V. Rzhanov Institute of Semiconductor Physics (Russian Federation)

Paper numerically investigates the excellent waveguide crossing by making the optical beam to pass over the intersecting silicon wire waveguide. Recently similar conception of vertical waveguide coupler with -0.2 dB loss from a bottom SOI channel waveguide to a top a-Si channel waveguide had been realized. Impedance matching is provided by contra directed inverse tapers in the respective waveguides. This design is good suited for waveguide crossing but needs advanced technology for a-Si manufacturing of over layered waveguide as well as carefully adjusting in space of two nano-tapers. We propose the simpler (in technology) design of wire crossing by means of vertical up and down coupling through the silica buffer of tapered Si wires with upper polymer strip waveguide constructed by

SU-8 (with refractive index 1.56). For the typical case of silicon wire with height 220 nm and width 450 nm the optimum structure has the following parameters: the silica buffer - 180 nm, the taper length and tip - 30 mkm and 160 nm, SU-8 polymer height and width - 1.7 mkm and 1.5 mkm, respectively. At central optical wavelength 1.55 mkm it provides the total internal loss about 0.1 dB for the through path: silicon wire – upper polymer – silicon wire. Crossing has negligible power reflection (-50 dB) and scattering into crossing waveguide (-70 dB). Thus it provides possibility for the several silicon wire crossings at moderate loss.

For the cross pass direction the optical wave pass through the straight silicon wire which is isolated from the crossing waveguides by the silica buffer. Thus it senses the present of the crossing waveguides only by the evanescent field. It provides negligible loss and possibility for multi-hundreds waveguide crossings in the cross pass direction. In order to study the tusk of light propagation through such multiple crossings we use the modified method of lines and the effective index method approximation. The main complexity of this task is in a small level of scattering field. Thus we have to increase the modeling accuracy by increasing the approximation order in the method of lines as well as by using the cascading effect and the symmetry of reflecting centers. Our results were tested by the numerical experiments by direct modeling by 3D finite difference time domain (FDTD) method. The simulations prove that proposed structure provides almost lossless silicon wire crossing (<0.002 dB). New waveguide crossing could be manufactured by CMOS compatible technology and can find wide application in silicon photonics for the cases if multiple and nondestructive waveguide crossing are needed for the high device performance. This work is funded by the RFBR project 12-07-00018-a.

8781-38, Session PS

Recent progress in opto-mechanical design of cavity developed for the OSQAR experiment

Karolina Macúchová, Jan Hosek, Sárka Nemcova, Czech Technical Univ. in Prague (Czech Republic); Miroslav Sulc, Technical Univ. of Liberec (Czech Republic); Josef Zicha, Czech Technical Univ in Prague (Czech Republic) and Czech Technical University in Prague (Czech Republic)

In this paper we present a current state of the OSQAR experiment. The search for axions or axion-like particles has reached its attainable level of conversion probability limited by parameters of the experimental setup used during the 2012 run. The photon-to-axion conversion probability limit is pushed further by increasing the value of contributing parameters. We focused on increasing the number of photons and their endurance time within the magnetic field using a laser cavity. Presented paper covers recent state of development of a prototype of a 1-m long laser cavity which is the prerequisite of further development of the experiment.

8781-39, Session PS

Accurate determination of initial value of theoretical evaluation of rare earth doped fiber lasers with high reflectance

Fatemeh Kazemizadeh, Tarbiat Modares Univ. (Iran, Islamic Republic of); Fatemeh Shahshahani, Alzahra Univ. (Iran, Islamic Republic of)

A method for accurate prediction of theoretical evaluation of rare earth doped fiber lasers initial value with high reflectivity valid for both four-level and three-level systems is introduced in this paper. In this method eliminating iteration process causes the reduction in computation time of solving the rate equations in respect to the standard model. The proposed method has been used for numerical evaluation of an erbium doped fiber laser with end reflectivity higher than 0.6. It is shown that the simulation results with the theoretical standard models are compatible and the relative difference between two models is approximately lower than 10 percent. It has been shown that the new proposed method can be improved by optimization of output mirror reflectivity.

8781-40, Session PS

Near-infrared elastic light scattering by a silicon microsphere

Ulas S. Gokay, Ali Serpengüzel, Koç Univ. (Turkey)

We observed elastic light scattering from a silicon microsphere in near infrared wavelengths. We utilized a tunable diode laser operating in the standard telecommunication band as the excitation source and a single mode silica optical fiber helped delivering of the laser light. The silicon microsphere was then carefully manipulated on the silica optical fiber half coupler (OFHC) to effectively couple the laser light to the microsphere thus exciting the whispering gallery modes. In this sense, the optoelectronic control and modulation of the refractive index of the silicon microsphere opens up novel device geometries for silicon microsphere based optoelectronic devices, such as filters, modulators, and detectors, leading to all optical computers and communication systems based on silicon photonics.

8781-41, Session PS

Determination of Amplifying Parameters of LMA Yb:silica Fiber Amplifier

Maryam Ilchi-Ghazaani, Parviz Parvin, Sajjad Mohammadian, Amirkabir Univ. of Technology (Iran, Islamic Republic of)

Today, the most popular power scaling techniques include pump enhancement, coherent and incoherent beam combining and the master oscillator-power amplifier (MOPA). MOPA array usually consists of an oscillator with axial diode laser pumping through the clad. The seed signal enteres into the core of the amplifier to attain the proper condition. The signal becomes intense traversing through the amplifier and suppresses the amplified spontaneous emission (ASE) along the fiber. Here, a continuous-wave (CW) single-mode (SM) double-clad (DC) Yb-doped silica fiber MOPA at 1082.5nm has been fabricated and optimized for experimental measuring the small-signal gain (?0) and saturation power (Psat) parameters.

The experimental setup is an all-fiber monomode narrow-linewidth laser array which operates at CW regime. The alignment of the system was implemented by fusion splicing of all optical components. In the master oscillator a fiber-coupled laser diode was employed to provide up to 4 watts output power at 976nm. The active fiber Yb1200 [N(m-3) = 1.2?1026] was employed as gain fiber, which had a mode field diameter (MFD)/inner cladding diameter of 6/125?m (NA=0.15/0.46) with octagonal microscopic cladding geometry. The laser cavity was formed by a pair of FBGs which one of them was used as the high reflector [R1(1082nm)=99.9%] and the other as the output coupler [R2(1082nm)=10%].

A polarization-independent fiber-to-fiber isolator with 30-36dB isolation loss was utilized to eliminate the signal back-reflections at the fiber end-face. Splicing a SC HI1060 passive delivery fiber to the laser end-face stripes residual pump power and provides pump dump. In the amplifier setup, a (6+1)?1 combiner is used to inject the signal seed of laser and simultaneously the pump wave.

After implementation of MOPA array, the seed signal into the amplifier was varied and the output signal was subsequently measured for various pump powers. The output powers are attributed to ASE, which is significantly at low input signals to the amplifier. Enhancing the amplifier pump power, the stimulated emission rate exceeds the threshold at higher input signals. The gain and saturation parameters were determined by fitting the experimental data on the steady-state amplification relation based on the least-square method which is well fitted to the experimental data.

The variation of the ?0 and Psat versus the pump power has been considered too. In the case of the low power fiber amplifier, the ?0 linearly depends on the pump power. Hence, the pump linearly increases the inverted population leading to linearity of gain with the pump power. On the other hand, the Psat linearly increases in terms of the pump power due to the signal filling factor ?s. In the communication fiber amplifiers, ?s is equal to unity due to the single-clad structure and Psat is linearly proportional to the pump power. For DC fiber amplifiers, ?s is smaller than unity. In other words, for the stronger pump power, the larger area of cladding is covered with the pump mode and therefore, ?s decreases leading to a linear increase of Psat with pump powers.

8781-42, Session PS

Fabrication and evaluation of chalcogenide glass molding lens for car night-vision system

Du Hwan Cha, Yeon Hwang, Hye-Jeong Kim, Jeong-Ho Kim, Korea Photonics Technology Institute (Korea, Republic of)

Thermal imaging in the 8 to 12 um wavelength range was once the sole domain of the military because of the high cost of the hardware (mainly detector). With the recent development of less costly uncooled infrared detector technology, thermal cameras have been applied to a wide variety of commercial applications such as night driving, night security, and sleep lab monitoring. However, the optics, made of expensive single-crystal materials such as Ge, Si, and ZnSe, still prohibit a breakthrough for high-volume commercial systems. In addition, the key process used thermal imaging lens fabrication is single-point diamond turning (SPDT). SPDT is an expensive operation and is not compatible with high volume applications. Therefore, it is unlikely that the cost of single-crystal lenses fabricated with SPDT can be dramatically decreased to meet the price target for applications such as night vision for cars. As a potential solution to this problem, the fabrication of IR lenses using chalcogenide glasses has been studied in recent years. Because chalcogenide glass is cheaper than the crystalline materials and moldable vitreous material, the use of a chalcogenide glass lens would be an effective way to reduce the cost of IR optics in high-volume applications. Molding is much cheaper than mechanical turning. However, the physical properties of chalcogenide glasses are very different from the optical glasses commonly used in glass molding. Therefore, extensive studies are required to determine the optimum parameters for molding this glass.

We report on fabrication of chalcogenide glass molding lens for car night-vision and on the evaluation of the molded chalcogenide glass lens. Molding conditions of the lens was determined by thermal analysis; molding temperature, heating time. The moldability of chalcogenide glass was characterized through defects of lens surface and transcription properties of the mold's surface. In addition, both IR transmittance and XRD patterns of the molded chalcogenide glass lens were evaluated to verify the compositional and structural stability of the glass material at the corresponding molding condition.

8781-43, Session PS

Modeling of CW Yb-doped Silica Fiber Laser by Considering Loss Mechanism

Maryam Ilchi-Ghazaani, Parviz Parvin, Amirkabir Univ. of Technology (Iran, Islamic Republic of)

Intensified research activities have been devoted to characterize rare-earth-doped fiber lasers in recent year. Owing to their compactness, superb beam quality and high pump efficiency, fiber lasers have become important light sources in medicine, modern telecommunications, industry, and so on.

At present, the rate equations are still the most powerful tools to theoretically and numerically predict the laser characteristics. It is worthwhile to mention that the laser loss is not negligible in a factual laser system. Therefore, analytical or numerical analysis on the output performance is essential in order to consider the distributed loss and non-uniformly pumping along the laser length. Previous papers concerning loss focused mostly on scattering loss coefficient for the laser radiation and the background loss of the pump wave in Yb-doped fiber lasers and presented experimental, analytical or purely numerical works. Hence, several errors have been occurred especially in high power regimes.

Compared with the known numerical analysis in published literatures, our model is more accurate. Considering imperfection splice points and combiner loss have never been explained before. We aim to compare this modified configuration with the more common scheme which does not include losses.

A set of coupled steady-state equations is introduced, along with the definition of the relevant parameters. We bring some numerical examples for Yb-doped fibers using the Runge–Kutta method and the shooting technique, considering the effect of imperfection loss efficiency of optical components using modified numerical analysis of a homogeneous, quasi-two-level gain media according to the atomic energy structure of dopants in an actual fiber laser. We have developed a numerical model for the rate equations that can describe the non-uniformly evolution of the multimode pump along the inner-clad and the interaction with the single-mode field propagating through the single-mode Yb-doped core.

Secondly, simulation results on the dependence of the upper state population, pump and signal as well as forward and backward ASE powers are discussed at different fiber location. The dependency of pump reflection, fiber length, and dopant concentration of Yb-doped DC fiber on the laser performance are investigated. The results have shown that the lasing threshold, slope efficiency and the optimum laser length strongly dependent on losses especially in homemade systems.

Also, the exact rigorous numerical solutions of the rate equations are shown to be in excellent agreement with the experimental results of fiber laser which prove the accuracy of the analysis. Under the strongly pumped condition, the effect of ASE in fiber amplifier is weak and thus can be neglected.

Afterward, the laser output power emerging from the R2=0.1 mirror is drawn as a function of the pump power injected at z=0. A comparison is also made between the experiment and accordant numerical data with and without loss. The expected linear increase of the output power with the pump is obtained. The output power can keep a monotonous increasing trend from 1–4W pump power with the slope efficiency of 63% after the output coupler, while spontaneous emission is responsible for exponentially power growing in low power regime.

8781-44, Session PS

Competition between Various Techniques for Power Scaling of Fiber Laser Output Power

Maryam Ilchi-Ghazaani, Parviz Parvin, Vajiheh Daneshafrooz, Amirkabir Univ. of Technology (Iran, Islamic Republic of)

Single longitudinal mode, single-polarization beam generates from a polarization maintaining double-clad (DC) Yb-doped silica fiber laser with high beam quality is more applicable for inertial confinement fusion application. Here, we investigated and analyzed several designs such as master oscillator-power amplifier (MOPA), parallel oscillators array as well as distributed array multifiber series fiber laser for scaling up the power of Yb:silica fiber laser in forward pumping regime.

Beam combination techniques where multiple low power lasers are efficiently combined in a multifiber beam combiner providing a single high-power output beam are being actively researched. The distributed array multifiber series fiber laser is proposed by Yan and coworkers in 2005. The fiber laser is composed of several side-pumped fibers and spliced spots. The side-pumped fibers are connected in series by fusion splicing. The fiber Bragg gratings (FBGs) set on the ends of the connected fiber is used as reflectors for the laser cavity. In MOPA structure, the laser seed is transmitted into the fiber amplifier core and the pump light is injected into the inner-clad.

The rate-equations were solved iteratively for the DC Yb:silica fiber laser and amplifier. The calculations were run numerically in fourth-order Runge–Kutta method and shooting technique was used for initial conditions. In multifiber design, we have four-parallel fiber laser that the pump power of each independent oscillator is 50W. The pump power is transmitted from 10m length of the gain medium and the output signal power of a single laser is ~37W. In distributed array scheme, the total fiber length of 40m is divided to four equal sections and each part is side pimped individually. In MOPA, the laser seed is amplified through three stages. The pump and signal losses at the splicing points are the significant mechanisms that limit the maximum of output power. The numerical simulation shows that the efficiency in distributed array method is higher than the multifiber design and is approximately equal as MOPA technique but in the experimental point of view, the MOPA array proposes.

Although, the distributed array will lead to a monolithic fiber laser without the requirement of further development of high-brightness diodes and has advantages as easy to manufacture, high efficiency, and power scaling, but also, scaling up the output power of the fiber laser is restricted with the damage threshold of FBG. It was shown that the effective loss in MOPA technique increases along the fiber

length due to the enhanced signal power based on Kerr loss effect, particularly at the end section of fiber near output coupler, while the loss in distributed array technique is uniformly high throughout a high power fiber laser resonator enhanced by a pair of FBG at both ends. In fact in MOPA, the thermal loss appears at end section of the fiber length, whereas in the distributed array, the loss appears all over the fiber length. As a result the total loss in MOPA is significantly smaller than those in distributed.

8781-45, Session PS

Astronomical optical frequency comb generation with silicon nitride micro ring-resonators

Tino Fremberg, Leibniz-Institut für Astrophysik Potsdam (Germany)

Astronomical optical frequency combs are regarded as the required tool for next-generation high-precision spectrograph calibrator. For maximum efficiency it is necessary to achieve equidistance of the comb modes, high stability, and wide spectral coverage. We experimentally investigate comb generation based on dispersion engineered micro ring resonators made of silicon nitride. This integrated waveguide approach renders it possible to use much more compact systems in comparison to comb generation in fibres or via mode-locked femtosecond lasers.

The silicon nitride ring resonators have propagation losses of about 1 dB per cm, enabling to confine the light for many roundtrips in the cavity. The diameter of the ring resonators is 250 and 500 micrometers while the transversal dimension is of the order of magnitude of several microns.

Different resonator designs are tested: 1) standard ring-resonator; 2) resonators with waveguide coupled feedback; and 3) concentric resonators with a gap between rings of 400 nm. With the designs 2) and 3) the coupling enhances the nonlinear interaction and reduces the required input pump power. To further enhance the comb generation, the dispersion was engineered by adding two extra cladding layers with appropriate thicknesses.

By using a continuous wave laser operating at 1550 nm as the pump source, we compare the bandwidth of the generated frequency comb in the three different types of resonators. We experimentally demonstrate, for the first time to the best to our knowledge, that dispersion engineered waveguides produce a much broader optical frequency comb if compared with the‘standard’ring resonators. Finally, a variety of pump phase-modulation schemes were tested to understand the effect of the presence of initial sidebands on the comb generation dynamics.

8781-46, Session PS

Numerical investigation of propagation constant in silicon nitride waveguides with different refractive index profiles

Daniel Bodenmüller, Leibniz-Institut für Astrophysik Potsdam (Germany)

The engineering of the group velocity dispersion of silicon-nitride-waveguides with a silica-cladding is investigated through numerical simulations. Three different types of waveguide structures are examined, which differ in their transversal index profile. For every type of waveguide a set of parameters is given (refractive index and thicknesses), which define the form of the index profile. The dispersion is investigated as a function of these parameters over a wavelength-range of 1.0µm to 2.5µm. In addition to the simple case of a waveguide with a Si_3N_4 core and silica cladding, more structured waveguides are taken into account, which contain two extra cladding layers of a certain thickness and with a refractive index that varies from 1.03 times silica-index to 0.97 times silicon-nitride-index. By the use of cladded core it is possible to change the shape of dispersion as a function of the wavelength in a wide range. We have adjusted the parameter set of the corresponding waveguide in order to reduce the variation of dispersion for the TE-mode along a wide wavelength range. For a cladded waveguide type variation of +-3ps/nm*km over a wavelength range from 1.8µm to 2.4µm was achieved. From this optimum dispersion profile we analyzed how the chromatic dispersion is modified/affected by varying the parameters independently from each other. As a third type of waveguide a silicon-nitride cladded core with a thin strip of silica between cladding and core has been simulated. For this structure a modification of thickness of the silica strip produces a change on the dispersion profile. The extent of change varies only slightly over the considered wavelength region and the effect on the curvature and slope of dispersion curve can be compensated by an appropriate adjustment of other parameters. As a consequence the authors were able to do a transition from low, flat dispersion to high, flat dispersion with a flat dispersion at all interim stages. Starting from a dispersion of around -90ps/nm*km with a variation for +-1.5ps/nm*km ends up at a dispersion of 60ps/nm*km with a variation of +-5ps/nm*km over a bandwidth of around 1µm respectively. Furthermore, we describe the dispersion properties of the TM-mode as well as the effective mode area of the optimized waveguides. Our results demonstrate that dispersion can be engineered in integrated waveguides at a comparable level of precision as it is currently done with photonic crystal fibres.

8781-47, Session PS

Optical characterization of the aperiodic multilayered anisotropic structure based on Kolakoski sequence

Volodymyr I. Fesenko, Institute of Radio Astronomy of NASU (Ukraine) and Kharkov National Univ. of Radio Electronics (Ukraine); Igor A. Sukhoivanov, Univ. de Guanajuato (Mexico)

The Kolakoski self-generating sequence was introduced in 1965 by William Kolakoski. Today, Kolakoski sequence has attracted the interest of computer scientists as well as mathematicians, but in respect to quasiperiodic/aperiodic photonic structures the Kolakoski sequence wasn’t investigated. As a rule, in the 1D case, quasiperiodic photonic structures are formed by stacking together layers of several different types according to substitutional sequences such as Fibonacci, Thue-Morse, Rudin-Shapiro or Cantor.

The simulation results of the optical transmission/reflection spectra in aperiodic multilayered anisotropic photonic structures that are arranged according to the Kolakoski sequence are presented in this paper. Spectral properties of two types of Kolakoski (KL) structures in the near-infrared region between 800 nm and 3000 nm are calculated by using a theoretical model based on the method of the electromagnetic field’s scalarization and the finite difference technique. The influence of the media anisotropy on optical properties of the structure is studied. The correlation between the geometrical and spectral properties of a generalized Kolakoski multilayer structure is found out.

As demonstrate our results, KL structures are found to have some peculiar spectral properties, notably rigorously defined band gap regions and lots of transmission peaks, which give an opportunity for a number of applications to be implemented on their basis. For instance that could be exploited in optical filters, laser systems, multi-frequency application and etc. Also Kolakoski multilayers are exhibiting various spectral properties that depend on the polarization of the incident electromagnetic plane wave, propagation direction of the electromagnetic wave, angle of wave incidence and chosen of the initial building “block” of the sequence.

8781-48, Session PS

Superprism effect close to the Bragg condition: a theory that maximizes the effect

Vito Mocella, Pierfelice Ciancia, Istituto per la Microelettronica e Microsistemi (Italy); Giuseppe Cocorullo, Univ. della Calabria (Italy); Ivo Rendina, Istituto per la Microelettronica e Microsistemi (Italy)

An approach based on the Dynamical Diffraction Theory (DDT) is presented in order to derive an analytic formulation of a superprism

effect and maximize that exhibit an extremely high angular dispersion. Superprism is characterized by an angular dispersion stronger many times than a conventional prism. In general it is possible to obtain different angular dispersions working on different PhC structures and materials. In the superprism literature the angular deviation is, usually, obtained using a purely numerical approach based on the shape of EquiFrequency Surface (EFS). We demonstrate that, working around the Bragg condition, it is possible to derive a formula of angular deviation that is in excellent agreement with Finite Difference Time Domain (FDTD) numerical simulations.

We apply the theory to a one dimensional Photonic Crystal (1D-PhC) at the main wavelength of 1.55µm. We demonstrate that it is possible to obtain an angular dispersion of 9.73°/nm by an easy manufacture structure of Si/SiGe that represent one of the most higher dispersion available in literature.

[1] S. SAVO, E. DI GENNARO, C. MILETTO, A. ANDREONE, P. DARDANO, L. MORETTI, MOCELLA V (2008). Pendellösung effect in photonic crystals. OPTICS EXPRESS, vol. 16-12, p. 9097-9105

[2] MOCELLA V, P. DARDANO, L. MORETTI, I. RENDINA (2007). Influence of surface termination on negative reflection by photonic crystals". OPTICS EXPRESS, vol. 15, p. 6605-6611.

[3] MOCELLA V, Y. EPELBOIN, J.P. GUIGAY (2000). Dynamical theory for a locally plane wave. ACTA CRYSTALLOGRAPHICA. SECTION A, FOUNDATIONS OF CRYSTALLOGRAPHY, vol. 56, p. 308-316.

8781-49, Session PS

Dot distribution type of grayscale photomask and colorscale photomask for single mask fabrication diffractive and refractive microlens

Qingle Tang, Huazhong Institute of Electro-Optics (China)

Recently, with the rapid development of the micro-fabrication technique of micro-optical devices and miniaturized optical systems with the feature size of micrometer or even small to nanometer, micro-optical structures, for instance, typical refractive and diffractive microlenses and micro-mirrors for main applications in optical communication, MOEMS, optical integration, military and biomedical imaging, wavefront detection, optical display, and optical data storage, etc., are finding increasingly widespread applications. So far, many methods to fabricate high quality microlenses with binary or continuous profiles, for example, photo-sensitive or thermal-sensitive shaping, hot- or UV-embossing, injection mounding, molding or casting, combination UV-photolithography with thermally reflowing, holographic exposure, sol-gel process, sputteringly etching or milling by ion beam, ion exchanging, X-ray or high energy beam lithography, micro-contact printing, directly writing by modulated lasers or e-beam, diamond turning, chemical or electrochemical process, and micro-structural formation by filling preshaped concave template with desired optical materials, etc., have already been extensively employed. Generally, the technique involving the conventional ultraviolet photolithography for prototyping photoresist microlenses leading to substrate microstructures needed, which defines the critical feature size and the layout of three-dimensional patterned structures, should be close to the demands of commercial mass production because of a longtime and relatively mature development of integrated microelectronic industry. However, for numerous applications of microlenses, the requirements including further simplifying technological flow, reducing production cost, shortening preparing and performing time, promoting fabricating precision, improving optical performance, forming feature microstructures over the curved surface of substrate treated, and having better compatibility with standard integrated circuit technology, etc., have continuously motivated investigators to explore more simple and reliable means.

Current researches show that the grayscale photomask techniques based on different working principles are inherent of very high resolution, and suitable to fabricate many kinds of micro-optics structures such as microlens, waveguide, and fine grating, etc[1-6]. So far many grayscale formation approaches including the micromirror projection display, the high energy beam sensitive glass photomask, the halftone photomask, the modulated scanning laser beam or e-beam method, the ion exchange processing, etc., have been developed. But mapping the layout of functional microstructures in photomask is usually a nonintuitive, complicated, time consuming, and expensive process.

The method based on microdrop distribution controlled by computer shows some attractive and competitive features compared to grayscale techniques mentioned above, such as low computational and fabricating cost, rapid arrangement of grayscale or colorscale microstructures, and allows for a more easily and rapidly understanding of designing requirements and parameter selection, because of the rapid advance of micro-jetting technology with precisely positioning function. The approach, which utilizes the grayscale or colorscale microstructures introduced in this paper, has a fine positioning and aligning accuracy in implementing pattern transferring, and then the pattern shaping errors can be remarkably decreased, and thus relatively complex micro-structures can be fabricated through common and inexpensive photolithographic facilities, so as to offer a potential of meeting the demands as above. In Sec. II, a grayscale model is established for describing the penetrating behaviors of UV-light in photolithography operation. In Sec. III, the colorscale technique for photomask is shown, which is similar to grayscale case. Finally, a brief summary is given.

3.Summary

By orderly distributing basic grayscale or colorscale microstructures introduced by us over polymer film for soft photomask utilized in single-mask photolithography, the pattern structures with multiple phase levels or smooth surface profile, which corresponds to the diffractive or refractive microlenses, respectively, can be obtained easily. According to the theoretical model and experimental relations between the transmitting power of UV-light and color with different brightness, the pattern structures with circle or non-circle (envelope) profile can be formed. It can be expect that the grayscale and colorscale technique based on microdrop jetting principle will play an important role in the mass production of many micro-optical structures.

References

[1] Thomas Dillon, Anita Sure, Janusz Murakowski, and Dennis Prather, "Continuous-tone grayscale mask fabrication using high-energy-beam-sensitive glass", J. Microlith. Microfab. Microsyst. 3, 550-554(2004).

[2] Brian Morgan, Christopher M. Waits, John Krizmanic, and Reza Ghodssi, "Development of a Deep Silicon Phase Fresnel Lens Using Gray-Scale Lithography and Deep Reactive Ion Etching", JOURNAL OF MICROELECTROMECHANICAL SYSTEMS 13, 113-120(2004).

[3] Glenn H. Chapman1, Yuqiang Tu, Chinheng Choo, Jun Wang, David K. Poon, and Marian Chang, "Laser-induced Oxidation of Metallic Thin Films as a Method for Creating Grayscale Photomasks", Proc. SPIE 6153, 61534G(2006).

[4] Zhaolin Lu and Dennis W. Prather, "Total internal reflection–evanescent coupler for fiber-to-waveguide integration of planar optoelectric devices", OPTICS LETTERS 29, 1748-1750(2004).

[5] Jeremy D. Rogers, Tomasz S. Tkaczyk, and Michael R. Descour, "Removal of ghost images by using tilted element optical systems with polynomial surfaces for aberration compensation", OPTICS LETTERS 31, 504-506(2006).

[6] Jeremy D. Rogers, Ari H. O. Kärkkäinen, Tomasz Tkaczyk, Juha T. Rantala, and Michael R. Descour, "Realization of refractive microoptics through grayscale lithographic patterning of photosensitive hybrid glass", OPTICS EXPRESS 12, 1294-1303 (2004).

8781-50, Session PS

Performance comparison between 33RZ-POMUX-DQPSK and 33RZ-DC-DQPSK using coherent detection for 1.6 Tb/s WDM transmission over 1200 km

Abir Hraghi, Univ. of Carthage (Tunisia) and National Engineering School of Communication of Tunis (Tunisia); Mourad Menif, Univ. of Carthage (Tunisia) and National Engineering School of Communication of Tunis (Tunisia) and SUP'COM (Tunisia)

Due to the increase in data traffics, a continuous raise in the network capacity is required by designing new modulation formats, which are playing a critical role in high bit rate transmission systems, in order to reach the 100 Gb/s transmission. Modulation formats that were used for 10 to 40 Gb/s transmission cannot simply perform for 100 Gb/s due to the limited optoelectronics bandwidth and the optical signal to noise ratio (OSNR). Thus, extensive works on searching modulation format for 100 Gb/s have been performed [1,2].

In this work, we implement two new optical modulation formats for the 100 Gb/s transmission systems and evaluate their efficiencies for the back-to-back and optical fiber transmission configurations. In fact, we investigate the performance of Polarization Multiplexing-Differential Quadrature Phase Shift Keying (POLMUX-DQPSK) and Dual Carrier-Differential Quadrature Phase Shift Keying (DC-DQPSK) with RZ (Return-to-Zero) carving and duty cycle of 33% in 100 Gb/s transmission systems. These formats appear to be the most promising technology for long-haul with coherent detection. POLMUX-DQPSK format uses the polarization dimension of the optical signal to transmit the information while the DC-DQPSK format uses two wavelengths to transmit the information. We discuss their back-to-back receiver sensitivity and required OSNR for a Bit Error Rate (BER) equal to 10-9. We find that 33RZ-POLMUX-DQPSK exhibits the best receiver sensitivity and lower OSNR penalty compared to 33RZ-DC-DQPSK. Considering the 33RZ-DC-DQPSK sensitivity as a reference, we determined a benefit of 1.5 dB for 33RZ-POLMUX-DQPSK. Therefore, a gain of 2.3 dB in OSNR for 33RZ-POLMUX-DQPSK compared to 33RZ-DC-DQPSK is obtained.

We study the robustness of these two optical modulation formats for bit rate transmission of 1.6 Tb/s (16100 Gb/s) over a distance of 1200 km in dispersion compensated WDM systems with 100 GHz channel spacing using two types of optical fibers : Single Mode Fiber (SMF) and Non-Zero Dispersion Shifted Fiber (NZDSF). We find that 33RZ-DC-DQPSK is a suitable modulation formats in dispersion compensated WDM systems with 100 Gb/s channel spacing using the NZDSF. By simulating the nonlinear tolerance of the optical 33RZ-POLMUX-DQPSK and 33RZ-DC-DQPSK formats, we demonstrate that the 33RZ-DC-DQPSK modulation format is more robust to the nonlinear fiber effects in the NZDSF.

8781-19, Session 5

A fresh look at integrated optical isolation and Lorentz reciprocity *(Invited Paper)*

Mathias Vanwolleghem, Institut d'Électronique Fondamentale (France) and Ctr. National de la Recherche Scientifique (France)

Taming the flow of backward scattered light has been a long time pursued goal in photonic circuits and optics in general. Integrating optical isolation in a light circuit has over the past three decades had to cope with serious technological and conceptual hurdles such as material growth and integration, bandwidth, insertion loss, polarization dependence and even power consumption. Though many solutions have been identified, the demonstrated integrated nonreciprocal photonic circuits with the best performance and operating specifications are still a distant cry removed from becoming a commercial viable product. The recurring bottleneck seems to be the integration of the magneto-optical material in the circuit. This has led several research groups over the last couple of years to look for alternative nonmagnetic approaches to break Lorentz reciprocity in an integrated circuit. Breaking time reversal symmetry without having to use magnetic fields or magnetic materials seems to be the way forward to finally achieve a fully Si photonics compatible integrated isolator/circulator, that is fully compatible with low-cost large scale integration. However, the physical concepts needed to achieve this, are subtle and can easily be misinterpreted. Several recent publications in high impact journals have falsely claimed nonmagnetic optical isolation. Maybe the traditional MO-based approach shouldn't be abandoned that fast ...

In this talk I will review the basic concepts of what makes and defines an optical isolator and what have been up till now the most successfully demonstrated magneto-optical integration schemes. Then I will move on by highlighting how reciprocity can be broken in nonmagnetic schemes. By illustrating both by a flawed result and an interesting new theoretical concept, I will indicate how simple time reversal breaking gets easily confused with nonreciprocity and why it is not possible to make a nonmagnetic isolator without at least an external source. In parallel the traditional magnetic schemes have also evolved, and ultra-compact (and possibly integration relaxed) approaches using plasmonic and resonant structures have been reported. In an outlook I will attempt to give a personal look on where integrated nonreciprocal research is headed and what may be expected for future integrated commercial isolators. This talk focuses on the challenges for nonreciprocity at optical and infrared frequencies. The recently in vogue mid-IR and THz portions of the spectrum have not even seen the beginning of nonreciprocal research. Some indications of where the challenges and opportunities lie here are also given.

8781-20, Session 5

Ultra-long, ultra-high quality fibre Bragg gratings

Raman Kashyap, Mathieu Gagné, Ecole Polytechnique de Montréal (Canada)

Since their discovery in 1978 by Hill et al., fibre Bragg gratings (FBG) have been highly successful as optical components for a large number of applications from sensing to telecommunications [1]. The distributed diffractive optic elements have several control parameters, such as length, strength of refractive index modulation, chirp and phase, which can profoundly affect performance of the optical filter to tailor a specific function. However, a limiting factor in the quality of the FBG, has been the quality of the phase-mask and the mechanical nature of the grating writing process. We recently reported a scheme that allows many of these limitations to be avoided, by using electro-optic UV phase-modulators that allow the synchronisation of a moving fibre with moving fringes [2], removing the inertial effects of the moving phase-mask, potentially allowing ease of tunability, apodisation and complex filter design. However, initial attempts at making high quality gratings proved to be extremely difficult. We solved this problem by proper engineering of the grating writing system and show that meter-long gratings of extremely high quality can be fabricated, with almost theoretically limited transfer characteristics for the first time. We report the fabrication and characterisation of these gratings with medium(~20dB) and ultra-high reflectivity (> 60dB). We compare the simulations with the experimentally measured characteristics with less than pm resolution. These FBGs show that the fibre is of extremely high quality with consistent properties over these long lengths. This technique demonstrates the possibility of making ultra-high quality complex filters for signal processing, opening possibilities for devices, not possible before.

References:

1. Kashyap, Raman, Fiber Bragg Gratings, Academic Press, 2009.

2. Mathieu Gagné, Lucian Bojor, Romain Maciejko, Raman Kashyap, "Novel custom fiber Bragg grating fabrication technique based on push-pull phase shifting interferometry," Optics Express 16(26), 21550-7, 22 Dec., 2008.

8781-21, Session 5

New insight in guided resonances with negative refracting photonic crystals

Silvia Romano, Consiglio Nazionale delle Ricerche (Italy); Ivo Rendina, Istituto per la Microelettronica e Microsistemi (Italy); Stefano Cabrini, The Molecular Foundry (United States); Vito Mocella, Istituto per la Microelettronica e Microsistemi (Italy)

Guided mode resonances (GMRs) in grating waveguide structures have been known since 1902 [1] and have been theorized for the first time by A. Hessel and A. A. Oliner in 1965 [2]. During these last years, many works have been devoted to analyzing and studying this phenomenon [3] and a large number of new applications appeared. In fact, GMRs can be employed in optoelectronic devices, such as optical filters or can be used as optical traps or sensors.

In this paper we present a new set of extremely accurate measurements of GMRs coupled in a 2D photonic crystal structure, with a negative refractive index at 1550 nm. Specifically, very sharp resonances are observable in the reflection spectrum characterized by a full-width (FWHM) of less than 2 nm. In addition to the classical measurements of the reflected signal, for the first time, we report the imaging of the radiation coupled into the structure, monitoring the light travelling into the structure with a IR camera. Finally, we present a new physical model of the phenomenon, which completes the already known phenomenological analysis [3]. The experimental data shows an excellent agreement with mentioned theory.

[1] R. W. Wood, Remarkable spectrum from a diffraction grating, Philosophical Magazine, 4:396, 1902.

[2] A. Hessel and A. A. Oliner, A new theory of Wood's anomalies on optical gratings, Applied Optics, 4:1275, 1965.

[3] Shanhui Fan and J. D. Joannopoulos, Analysis of guided resonances in photonic crystal slabs, Physical Review B, vol. 65, 235112, 2002.

8781-22, Session 5

Dispersion optimization of slow light in slotted photonic crystal waveguide by selective air holes infiltration

Ya-Nan Zhang, Yong Zhao, Qi Wang, Northeastern Univ. (China)

Slow light with a remarkably low group velocity has recently attracted wide attention because it is regarded as a promising approach for time-domain processing of optical signal and spatial compression of optical energy. It also offers the possibility for miniaturization sensors with high sensitivity. Photonic crystal waveguide (PCW) is especially attractive for generating slow light, which has many advantages such as room-temperature operation, great potential for wide-bandwidth, and realizing slow light at the scale of an optical wavelength. Particularly, the slotted photonic crystal waveguide (SPCW) could combine the ability to confine light in the nano-scale slot with the slow light enhancement available from PCW, which could be advantageously utilized in practical applications. However, in practical applications, the slow light in SPCW needs to be optimized with wideband and low dispersion to overcome the influence of environmental temperature, fabrication errors and large group velocity dispersion (GVD). As the useful bandwidth lies below the silica light-line, it is a challenge to tailor the dispersion band for constant group index transmission with a wide bandwidth and it is also difficult to linearize the dispersion band close to the band edge where the GVD diverges.

This work proposed a methodology based on the liquid infiltration of SPCW. The infiltration of liquids has a wide refractive index variety ranging between 1.3 and 2. By choosing the refractive index that infiltrated in the first and second rows of air holes adjacent to the slot respectively, SPCW was optimized to possess wideband slow light with large group index and low dispersion. The properties of SPCW were numerically simulated by plane wave expansion (PWE) method and finite-difference time-domain (FDTD) method using MIT's freely available software MPB and Meep. We first analyzed the dependence of the dispersion properties on the refractive index of the first two rows of air holes respectively. Based on this, the properties of slow light were subsequently explored and optimized. At last, the transmission and coupling properties of liquid infiltrated SPCW were discussed.

The simulation results showed that the designed SPCW could control the group index for the same SPCW with the nearly constant group index of 50, 85, 150, and 210 over 12nm, 8.1nm, 4.5nm, and 2.2nm, simply by choosing the refractive index of the infiltrated liquid. On the other hand, the operating wavelength could be tuned from 1550nm to 1562nm at the group index of 150 with substantial bandwidth for the same SPCW. In addition, the slow light property of the designed SPCW was tolerant to the deviation in the holes radii of SPCW and the temperature disturbance of surrounding temperature. At last, the coupling problem between traditional single mode fiber and SPCW was solved by introducing a resonant structure at both the input and output interface to improve the coupling efficiency, and the coupling coefficient could up to 82% over a 68nm bandwidth.

8781-23, Session 5

A parallel computational FDTD approach to the analysis of the light scattering from an opal photonic crystal

Alessandro Vaccari, Antonino Cala' Lesina, Fondazione Bruno Kessler (Italy); Luca Cristoforetti, Provincia Autonoma di Trento (Italy); Andrea Chiappini, Consiglio Nazionale Delle Ricerche (Italy); Francesco Prudenzano, Politecnico di Bari (Italy); Alessandro Bozzoli, Fondazione Bruno Kessler (Italy); Maurizio Ferrari, Istituto di Fotonica e Nanotecnologie (Italy)

In this paper it is described a computational approach for the analysis and the characterization of opal photonic crystals (PC). In particular these crystals are modeled by an ordered face-cubic centered (FCC) lattice structure of spherical particles with a given filling factor. These particles are made of a non-absorptive material with a specific dielectric permittivity. It is also possible to consider a dispersive material with a complex permittivity. The physical phenomenon of the multiple scattering of the impinging laser beam by the spheres is simulated through the numerical solution of the Maxwell Equations using the FDTD (Finite Difference Time Domain) method. The resulting field is calculated in a discretized fashion on a three dimensional grid of sampling points. Frequency Domain results are obtained by means of a Discrete Fourier Transform (DFT) of the system response to the transient excitation of the impinging pulse. The eventual frequency dependence of the objects' permittivity is accounted for in the time domain by modifying the formulation of the Ampère-Maxwell equation with a convolution integral describing the temporal dispersion in the relation between the D and E fields. Such a convolution integral can be calculated in a recursive way at every FDTD sampling point and then, with a single run of the FDTD code, one is able to get an entire frequency spectrum of results, at the cost of the computer memory needed to store the transformed electric field values at the various frequencies. The main purpose is to obtain the reflectance and the transmittance of the opal PC in the 500÷1000 nm wavelength range. The scattering by the spheres originates a non-omnidirectional pattern for the transmitted and the reflected light. Through an analytical approach (Kirchhoff's formula) this angular distribution is calculated. The structure, due to the nano-scale and to the space-discretization required for accuracy reasons, is cumbersome and challenging from a simulation point of view and a parallel approach is required for that. By using the Message Passing Interface API for the field components communication between processes and a cubic slicing for the decomposition of the analysis domain the simulation can be done on high performance computing (HPC) systems. The preliminary results highlight the presence of a band-gap in the transmission curve as a function of the wavelength in the 500÷1000 nm range. Although some modeling approximation has to be done the proposed numerical technique seems appear as a promising tool for the theoretical characterization of opal PCs. We are confident to obtain an agreement with the experimental measures carried out in our laboratory and besides to apply this simulation tool to the random close packing sphere configuration for the analysis of photonic glasses.

8781-24, Session 6

Low-power nanophotonics: material and device technology *(Invited Paper)*

Lars Thylén, Royal Institute of Technology (Sweden) and Hewlett-Packard Labs. (United States); Lech Wosinski, Petter Holmstrom, Sebastian Lourdudoss, Royal Institute of Technology (Sweden)

Low power nanophotonics has become a key technology, primarily due to the rapid expansion of the need for optical interconnects in data centres. In order to pursue the device performance development over the past decades, an assessment of material and device technology is necessary in order to meet systems requirements. The talk will treat the material scenario offered by combining III Vs, silicon, electrooptic polymers and plasmonics and give some examples of low power and small footprint devices and corresponding performance. The issue of all optical switching vs the electronically controlled version is also briefly discussed.

8781-25, Session 6

Energy-per-bit and Noise Limits in Plasmonic Intergrated Photodetectors

Pierre Wahl, Vrije Univ. Brussel (Belgium); Takuo Tanemura, The Univ. of Tokyo (Japan); Christof Debaes, Nathalie Vermeulen, Jürgen Van Erps, Vrije Univ. Brussel (Belgium); David A. B. Miller, Stanford Univ. (United States); Hugo Thienpont, Vrije Univ. Brussel (Belgium)

The energy consumption per transmitted bit is becoming a crucial figure of merit for communication channels in optical interconnects. In this paper, we study the design trade-offs in plasmonic photodetectors, utilizing the energy per bit as a benchmark instead of bandwidth or Bit Error Rate (BER).

It is well known that the minimum energy-per-bit at which a photodetector can operate is proportional to the total detector capacitance and inversely proportional to the detector quantum efficiency. Having this in mind, we propose a generic photodetector model which takes the detector's optical and electrical properties into account in the simplest useful approximation. In this model, we assume that all the light that reaches the photodetector is contained within a single optical mode. This framework includes waveguide-based photodetector designs where the light is coupled in through a single mode waveguide, as well as surface-normal designs where the incoming mode can be approximated by a plane wave. In addition, we assume a device without a resonant cavity. Hence, detector operation is based on the absorption of light as it travels through an absorbing medium for a certain length. Given a particular lateral geometry, this length determines the size of the detector. The longer this interaction distance, the more light is absorbed in a single pass. As the losses in the metal can also be calculated, this allows us to make an estimate of the quantum efficiency of the detector.

Also, the contacts are assumed to have a capacitance per unit of length while the front-end amplifier contributes to a fixed parasitic capacitance which does not depend on the length of the detector. This formalism allows us to estimate the total detector capacitance. As increasing the length of the detector increases the quantum efficiency and the capacitance, there is a length at which the detector shows an optimal energy per bit. Using our formalism, we show how the parasitic capacitance of photodetectors can drastically alter the parameter values that lead to the photdetector design with the smallest energy per bit.

We also provide an estimate of the noise power and the BER at which a plasmonic photodector optimized by our formalism would operate. This noise model assumes the use of a high impedance ("receiverless") front-end amplifier and includes thermal noise as well as shot-noise from the photocurrent, dark current and leakage current through the gate of the front-end transistor.

Finally, we apply our theory to a practical case study for an integrated plasmonic photodetector, where we simulate both the optical and electrical properties of the photodetector numerically. We show that energy per bit values below 100 attoJoules are feasible despite metallic losses and within noise limitations at 50 GHz for a bit-error rate of 10^-15. Finally, we show that this is possible without the introduction of an optical cavity or the use of voltage amplifying receiver circuits.

8781-26, Session 6

Analysis of novel plasmonic guiding nanostructures with Fourier modal methods

Pavel Kwieicen, Ivan Richter, Czech Technical Univ. in Prague (Czech Republic); Jirí Ctyroky, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic)

When incorporating surface plasmons-polaritons (SPP) in photonic designs and succeeding devices, one has to keep in mind that their unique properties, connected with the exceptional subwavelength-region localization and confinement, always go together with the inherent losses, which are always present within realistic metallic materials, and hence interposing serious trade-off design strategies for successful plasmonic devices. Hence nowadays, rigorous numerical techniques for reliable simulations and designs of such plasmonic nanostructures are of fundamental importance in the analysis and design of novel photonic devices. Clearly, these techniques should provide an efficient and accurate description of structure physical characteristics, based on light interaction with the devices, involving not only large refractive index contrasts, but also metallic highly-dispersive components. Moreover, as subwavelength-structured plasmonic nanostructures are recently becoming even more promising and versatile structures for various potential applications (e.g. in optical filters, switches, modulators, biosensors, lasers, etc.), subsequently, there is also a need for novel theoretical critical and reliable studies on these realistic three-dimensional (3D) designs. This work is thus firstly dedicated to the analysis of several concepts of dielectrically supported plasmonic waveguing structures. Based on our two completely independent efficient in-house 3D Fourier modal method (FMM) algorithms, relying on either aperiodic rigorous coupled wave analysis or bi-directional mode expansion and propagation techniques, we have investigated several novel guided-wave plasmonic nanostructure designs, including some alternatives of dielectric-loaded plasmonic and / or subwavelength-structured nanoguides. More specifically, the analysis of several types of hybrid dielectric-plasmonic slot waveguide (HDPSW) structures is presented, starting from single waveguides, with the optimization of their dispersion and geometrical parameters. Further, our effort will be devoted to understanding and exploitation of more complicated structures incorporating HDPSW concept, such as, e.g. plasmonic directional couplers, MMI filters, and Mach-Zehnder interferometer-based modulators. Such structures can indeed exhibit promising tradeoffs between confinement and propagation properties, and thus representing promising building blocks for future plasmonic devices. On the other hand, they embody very extensive and demanding computational problems, on which, however, our numerical techniques could be effectively applied. Results of modeling of such structures from our two FMM will be mutually compared, too. We will also discuss that their performance is practically equal, however, their subtle complementarities to efficient usage on specific problems is the advantage within our common efforts. Finally, we will also review possibilities of comparison of such SPW and devices, in terms of both field confinement and propagation abilities, in order to enable their effective direct performance comparison. Although there have been some suggestions, this issue still needs attention. Also, we have introduced a novel type of figure of merit (FOM), and compared it with the standard one. Additionally, we will also consider a possible generalization of HDPSW with periodically segmented blocks, supporting propagation of Bloch modes. More details and possibilities of such design will be discussed at the conference.

8781-27, Session 6

Energetic analysis of the plasmonic lens structure: a first step to simplification

Quentin Levesque, Patrick Bouchon, ONERA (France); Fabrice Pardo, Lab. de Photonique et de Nanostructures (France); Riad Haïdar, ONERA (France); Jean-Luc Pelouard, Lab. de Photonique et de Nanostructures (France)

The development of integrated compact optical sensors requires the miniaturization of lenses at a mesoscopic scale. The reduction by a homothetic transformation of conventional dielectric-based optical devices is limited by diffraction phenomena, which lead to a deterioration of their focusing capability. An alternative based on planar plasmonic lenses has been recently proposed [1,2]. Indeed, the optical index of a guided mode in a subwavelength metallic slit is tailored by simply tuning its width [3]. Thus, an array of subwavelength slits of different widths in a metallic layer induces a lens effect for a TM-polarized incident plane wave. However the realization of such devices requires etching an array of slits of various aspect ratios while keeping nanometric precision: a small deviation in their aspect ratio can significantly change the induced phase pattern. These technological constraints are hardly achievable, and underline the need for a simpler design.

For this purpose, we propose a two-step simplification of the design of plasmonic lenses, thanks to basic physical and technological assumptions. This template introduces the new concept of to Huygens lens that consists in the combination of a wide central slit surrounded by external single mode slits (technologically viable and convenient aspect ratios). Huygens lenses are no longer based on the guided mode index modulation but rather on wave interferences, which provide them good focusing performances [4].

In these structures, the central slit (width D0) localizes the focalization spot at the desired focal length F, given by the pinhole diffraction formula F=D02/(4?). Then, single mode slits are added on each side of the central aperture at positions that allow building constructive interferences at the desired focal length. We will show that the focalization is sharper for larger number of secondary slits, in agreement with the lens aperture theory. A Huygens lens was designed for a normally incident TM-polarized wave at a wavelength ?=633nm. It focalizes more than 40% of the transmitted energy into a spot of width 2?F/Dext where Dext represents the distance between the outermost slits at F=6µm. The energetic efficiency of the focalization is increased by a factor 2.1 achieving performances better than an equivalent "unsimplified" plasmonic lens [5].

[1] H. Shi et al., Opt. Express, 13, 6815-6820, (2005)

[2] L. Verslegers et al., Nano Letters, 9, No. 1, 235-238, (2009)

[3] S. Collin et al., Opt. Express, 15, 4310-4320, (2007)

[4] Q. Lévesque et al., in preparation.

8781-28, Session 6

Resonance effects in the optical antennas shaped as finite comb-like gratings of noble-metal nanostrips

Olga V. Shapoval, Institute of Radio-Physics and Electronics (Ukraine) and National Academy of Sciences of Ukraine (Ukraine); Jirí Ctyroky, Institute of Photonics and Electronics of the ASCR, v.v.i. (Czech Republic); Alexander I. Nosich, Institute of Radio-Physics and Electronics (Ukraine) and National Academy of Sciences of Ukraine (Ukraine)

Active research into nanoscience and nanomaterials and appropriate technologies that are available for nano fabrication have lead to considerable progress in the understanding of the optical properties of metals on nanometer scale. Here, noble-metal strip-like nanostructures are attractive object of research. Indeed, they can be easily manufactured and serve as building blocks of optical nanoantennas and sensors with unique geometry-dependent optical properties. This is because they display intensive localized surface-plasmon resonances (SPR) in the visible and far-infrared ranges that lead to near- and far-field enhancement effects.

In the optical applications, the typical dimensions of metal nanostrips are the width from 100 to 1000 nm and the thickness from 5 to 50 nm. Thereby, the strip thickness is some 10 to 180 times smaller than the wavelength in the visible band. Under such circumstances, the SPRs are the Fabry-Perot-like resonances formed by the reflections of the short-range surface plasmon wave of the corresponding metal layer from the strip edges. Therefore their wavelengths can be tuned by changing the strip width and thickness. In addition to SPRs, multi-element finite gratings have attractive properties of extraordinarily large reflection, absorption, and near-field enhancement (i.e. focusing) that are inherited from the wave scattering by infinite strip gratings. Namely, these phenomena are greatly influenced by the so-called grating resonances (GRs) which appear only due to periodicity. Unlike the SPRs, the GRs are relevant to the either polarization and exist across all types of strip materials and incident-wave wavelengths. They are important if the number of periods is in the range of at least dozens and hundreds although this depends on the strip dimensions and material composition.

The 2-D modeling of electromagnetic wave scattering and absorption by thin noble-metal (e.g., silver or gold) nanosize strips and their finite-periodical ensembles arranged in comb-like gratings is considered. Our analysis is carried out using new efficient, convergent and accurate method. It is based, first, on the use of the special type of generalized boundary conditions valid for a thin and high-contrast material layer; they allow us to consider only the limit values of the field components and reduce integration contour to the corresponding strip median lines. Second, for the building of discrete model of the obtained singular and hyper-singular integral equations, we use a very efficient Nystrom-type numerical algorithm with weighted quadrature formulas of interpolation type.

We study the SPRs of the individual nanostrips and their finite periodic comb-like ensembles versus the incidence angle of the incident plane electromagnetic wave and strip characteristics, such as strip thickness and width and gap size between the strips; both near-field and far-field properties of the associated SPRs and especially local field enhancement or focusing effects are analyzed. Moreover, we investigate the periodicity-induced properties such as the GRs, and combined co-existence of the SPRs and GRs resonances in the context of the development of optimal design strategies for efficient multi-strip optical nanoantennas.

8781-29, Session 7

Group IV platforms for the mid-infrared *(Invited Paper)*

Goran Z. Mashanovich, Milos Nedeljkovic, Xia Chen, Taha M. Ben Masaud, Univ. of Southampton (United Kingdom); Muhammad Muneeb, Univ. Gent (Belgium); Michael Strain, Marc Sorel, Univ. of Glasgow (United Kingdom); Thomas F. Krauss, The Univ. of York (United Kingdom); Gunther C. Roelkens, Univ. Gent (Belgium); Anna C. Peacock, Harold M. H. Chong, Graham T. Reed, Univ. of Southampton (United Kingdom)

The mid-infrared wavelength region offers several application areas including sensing, communications, security, medicine and astronomy. The most dominant platform in silicon photonics, that of silicon on insulator (SOI) can be used up to 4 microns due to high oxide losses at longer wavelengths. Therefore, alternative platforms need to be researched in the mid-infrared. In this paper we present silicon photonics devices such as rib, strip and PhC waveguides, MMIs, ring and racetrack resonators, Mach-Zehnder interferometers, and multiplexers fabricated in several material platforms. We report fabrication and characterisation of group IV photonic devices based on the following platforms: silicon on insulator, silicon on sapphire (SOS), silicon on porous silicon, polycrystalline silicon, germanium on silicon and suspended silicon structures. We discuss advantages and disadvantages of the platforms and suggest improvements in terms of device performance.

8781-30, Session 7

Silicon nitride back-end optics for biosensor applications *(Invited Paper)*

Sebastián Romero-García, Florian Merget, Jeremy Witzens, RWTH Aachen (Germany); Frank C. Zhong, Hod Finkelstein, Illumina, Inc. (United States)

We will present simulation results and measurements for a complete set of Silicon Nitride devices fabricated in the back-end of a CMOS chip with the goal of implementing a power distribution network in the visible domain. Devices include high-efficiency grating couplers, multi-mode interferometers and photonics waveguides.

8781-51, Session 7

Hybrid plasmonic microdisk resonators for optical interconnect applications

Fei Lou, Royal Institute of Technology (Sweden); Lars Thylén, Royal Institute of Technology (Sweden) and Joint Research Ctr. of Photonics (China) and Hewlett-Packard Labs. (United States); Lech Wosinski, Royal Institute of Technology (Sweden) and Joint Research Ctr. of Photonics (China)

The rapid performance growth of microprocessors leads to increased demands for chip-to-chip (processor-to-memory) and intra-chip (core-to-core) information flow. Signal speed and wiring density of electrical circuits are reaching their physical limits. To meet the challenges in data transfer, highly integrated optical interconnects are being employed that enable new system architectures. The next-generation

system designs in turn require new devices and new technology.

The trend is towards CMOS compatible silicon photonics, which means the reduction of material diversity as well as functional unification of photonic components. The size of these highly integrated structures is constrained by the diffraction limit of light. To go below this limit, plasmonic structures based on metal-dielectric interfaces have been proposed although their intrinsic high losses make their practical use with the available metal films impractical. Recently a new type of "hybrid plasmonic waveguides" was developed, that allows for similar light confinement as in a metal-dielectric guides [1,2], but with much lower losses allowing for much longer propagation lengths.

To meet interconnect and unification demands, integrated structures based on microring/disk resonators have been proposed. They can be configured as N ? M routers, add/drop multiplexers, switching matrices, delay lines and others.

In this paper we present a series of microdisk resonators for different applications based on hybrid plasmonic nanowire waveguides. Here a very thin, 56 nm low-index dielectric layer (called slot layer) is sandwiched between a metal (Au, 100 nm thick) from one side and a thick (400 nm) high-index dielectric material from the other side. In the fabrication process, a lift-off is firstly done by e-beam lithography (Raith 150 at 25 kV) using a positive resist (ZEP-520A), and a 100 nm thick gold strip is evaporated on top of a thick SiO2 box by electron beam evaporation. Then, a 56 nm SiO2 slot layer and a hydrogenated amorphous silicon (a-Si) with a thickness hSi = 400 nm are deposited successively by plasma enhanced chemical vapor deposition. After that, resonator patterns are generated by EBL using negative resist ma-N 2403. Note that careful dose tests are necessary in this step due to a strong electron scattering from a gold substrate. Then, an optimized inductively coupled plasma etching is used to transfer the patterns to the top silicon layer. In the last step, a thick polymer access waveguides are defined by EBL for coupling light between lensed fibers and the device.

With the described procedure a series of different microdisks was fabricated. The width of the access waveguides was 170 nm. The tilt angle of waveguide sidewalls was 88o. The measured waveguide loss was 0.08 dB/µm at 1550 nm. The smallest microdisks have diameters of only 1 µm, which are, according to the authors' knowledge, the smallest microdisk resonators ever fabricated. Spectral responses were measured for microdisks with different gaps. With silica as the low-index dielectric layer and silicon as the high-index dielectric material, this structure is totally CMOS compatible. The demonstrated devices can be potentially used in future photonic integrated circuits.

8781-32, Session 8

Ge/SiGe quantum well optical modulator
(Invited Paper)

Delphine Marris-Morini, Papichaya Chaisakul, Mohamed-Saïd Rouifed, Institut d'Électronique Fondamentale (France); Jacopo Frigerio, Politecnico di Milano (Italy); Giovanni Isella, Lab. for Epitaxial Nanostructures on Silicon and Spintronics (Italy); Daniel Chrastina, Politecnico di Milano (Italy); Xavier Le Roux, Samson Edmond, Jean-René Coudevylle, Laurent Vivien, Institut d'Électronique Fondamentale (France)

Silicon photonics is about to revolutionize the field of integrated optoelectronics. The recent demonstrations of optical modulators and photodetectors operating at 40 Gbit/s were inconceivable only a few years ago. The performances are such that new applications are being considered, such as communication between microprocessors cores and between servers in data centers. For many of these applications, the drastic reduction of the electrical power required to drive the modulator, to values typically less than 100 fJ/bit, is mandatory, together with a large optoelectrical bandwith, low optical losses and high modulation ratio.

In the solutions being developed, wide optical bandwith (no resonator) silicon optical modulators using carrier depletion require the use of an active region several millimeters long, resulting in significant power consumption, of the order of 10 pJ / bit. The realization of low power consumption optoelectronic devices is only possible by using innovative breaking concepts. In this context Ge/SiGe multiple quantum wells (MQW) structures appear as a promising solution. In the presentation we will report recent results on optoelectronic devices based on Ge/SiGe MQW including the first development of high speed, low energy electro-absorption modulator, high responsivity and high speed photodetectors compatible with 40 Gb/s data transmission, and the first light emitting diode based on Ge direct gap transition at room temperature.

8781-33, Session 8

Multi-scale simulation of an optical device using a novel approach for combining ray-tracing and FDTD

Claude Leiner, Susanne Schweitzer, Volker Schmidt, Maria Belegratis, Franz-Peter Wenzl, Paul Hartmann, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria); Ulrich Hohenester, Karl-Franzens-Univ. Graz (Austria); Christian Sommer, JOANNEUM RESEARCH Forschungsgesellschaft mbH (Austria)

Complex photonic systems generally interact with light on different length scales, ranging from sub-wavelength to macroscopic dimensions. A suitable physical model therefore requires different simulation approaches due to the trade-off between the numerical effort and the physically reasonable description of such a system, which has to account properly for various effects such as polar¬ization, interference, or diffraction: at dimensions much larger than the wavelength of light common ray-tracing techniques are conveniently employed, while in the (sub-)wavelength regime more sophisticated approaches, like the so-called finite-difference time-domain (FDTD) technique, are needed.

A proper description of physical light propagation on both scales, the (sub-)wavelength and the macroscopic regime, is only achieved by bridging between these two approaches. Unfortunately, there are no universally valid rules for switching from one method to the other, and the development of appropriate selection criteria is a major issue to avoid a summation of errors. Moreover, since the output of one simulation method provides the input for the other one, care has to be taken in order to ensure mathematical and physical consistency.

In this contribution we present an approach, which combines classical geometric ray-tracing with FDTD simulations. This enables a joint simulation of both, the macro- and the microscale including incoherent and coherent effects. By means of an optical setup, containing both a diffractive optical element (DOE) and macroscopic optical elements we will show the basic principles of this approach and the corresponding simulation criteria. In order to prove the physical correctness of our simulation approach, the simulation results will be compared to measurements of a real device. Beyond that, we will discuss further applications of this simulation approach for more complex devices containing multiple DOEs.

8781-34, Session 8

Adapted perfectly matched layers (PML) for diffraction gratings and their quasi-modal analysis

Benjamin Vial, Institut Fresnel (France); Frédéric Zolla, André Nicolet, Univ. d'Aix-Marseille (France); Mireille Commandré, Institut Fresnel (France); Stéphane Tisserand, Silios Technologies (France)

Nowadays, the Finite Element Method (FEM) is an effective method to compute diffaction gratings. It provides a tool that is extremely versatile and accurate (any kind of geometry and of material properties may be tackled, as well for the 2D gratings as for the 3D crossed gratings) at a reasonable computational cost. This has been made possible by the increase of power of the computers together with the improvement of the sparse matrix solvers but the numerical formulation of the problem has also played a determinant role: the "diffracted field" has to be defined carefully if the substrate and the superstrate are made of different materials (as in most of the practical cases), the quasi-periodic Floquet-Bloch conditions are used to reduce the problem to a single cell, and the Perfectly Matched Layers (PML),

introduced by Bérenger in 1994, are used for the truncation of the infinite domain above and below the groove region.

The PML are very efficient for waves with incidence normal to the PML but have a decreasing accuracy when these incident waves tend to be grazing, e.g. when Wood's anomalies arise. This is due to the fact that the corresponding apparent wavelength is increasing and the PML coefficient is no more adapted to this case. In this paper, we propose adapted PMLs with continuously varying parameters in order to absorb the waves of all incidences at various depth in the PML. A practical way to design such PMLs is to consider Transformation Optics (TO). PMLs may be obtained by applying a complex-valued stretch to the coordinates and then computing the resulting equivalent materials. It is therefore natural to compose this complex stretch with another coordinate transformation in order to obtain a non uniform PML adapted to the different orders of a given grating, i.e. using a geometrical transformation that sets the apparent wavelengths to values close to the fundamental wavelength of the problem. A transformation specific to the diffraction gratings is first proposed. Then, a second solution is proposed in the form of a general transformation that maps an infinite open region on a finite layer.

The spectral analysis of the diffraction gratings gives very interesting information about their behaviour (for instance, if we are interested in using them as filtering devices). Since they are open structures, they have to be analysed in terms of quasi-modes (associated to complex frequencies) and the design of the PMLs is crucial specially for the correct computation of the imaginary parts of the frequencies associated to losses and leakages. The role of the PMLs is to rotate the continuous spectrum in the complex plane in order to unveil the quasi-modes (by providing a non-Hermitian extension of the operator associated to the initial problem). As an application, a (quasi-)modal method (using a biorthogonal system) for the diffraction gratings will be presented.

8781-35, Session 8

Superfocusing and mirror transformation of airy pulses under the action of third order dispersion

Rodislav Driben, Tel Aviv Univ. (Israel) and Univ. Paderborn (Germany); Yi Hu, Institut National de la Recherche Scientifique (Canada); Zhigang Chen, San Francisco State Univ. (United States); Boris A. Malomed, Tel Aviv Univ. (Israel); Roberto Morandotti, Institut National de la Recherche Scientifique (Canada)

Truncated Airy pulses where launched in a fiber close to its zero dispersion point thus allowing the effect of third order dispersion (TOD) to play a dominant role in the dynamics of the propagating pulses. When the truncated Airy pulse propagates in presence of a pure quadratic dispersion it propagates for a finite distance until it reaches the area of divergence. However when a pure TOD with a positive sign governs the pulses dynamics, a somehow surprising result is achieved. The pulse quickly reaches the focal point, then undergoes a mirror transformation and continues to propagate, with its trajectory bended in an opposite direction. When both dispersion terms act on a pulse the focal point extends to a finite area of truncated Airy pulse "non-existence". The size of the area depends on the relative strength of the third order dispersion term when compared to its second order counterpart. Outside this area, the pulse re-emerges again being mirror transformed and continues its evolution. The combined effect of the second and third order dispersion terms makes Airy pulses with a small truncation parameter more robust after the mirror transformation. In a strongly nonlinear regime, we observe soliton shedding out of the Airy pulse structure, being the frequency of the ejected soliton controlled by the third order dispersion strength.

WS100-1, Session 1

HiPER Project: Status *(Invited Paper)*

Chris Edwards, Science and Technology Facilities Council (United Kingdom)

No Abstract Available

WS100-2, Session 1

LIFE Project: Overview *(Invited Paper)*

Mike Dunne, Lawrence Livermore National Lab. (United States)

No Abstract Available

WS100-3, Session 2

Experimental exploration of a cryogenically operated Yb:YAG laser prototype for inertial fusion laser programs *(Invited Paper)*

Jean-Christophe F. Chanteloup, Thierry Gonçalvès-Novo, Ecole Polytechnique (France)

The European inertial fusion reactor project HiPER is based on a laser program development relying on several key continental laboratories each exploring specific laser solutions. If the choice of gain medium, the thermal management solution, etc… differ, all have scheduled a somehow similar progressive energy ramping roadmap with intermediate energetic milestones on the path towards a 1kJ HiPER compatible beamline. At LULI, after having reach our 10 Joules first milestone (14 Joules where achieved in 2012 at 2 Hz) with our current Room Temperature (RT=300K) operated Yb:YAG laser head, we have in the past months commissioned a second amplifier stage for the Lucia laser chain. This laser head will operated at a temperature to be defined within the 100 to 200K temperature range. The cryostat is already operational. A dedicated 33kW pump source was delivered in fall 2012 and we have received our first co-sintered ceramic, still awaiting coating. This 77 mm diameter, 10 mm thick Cr4+/Yb3+ :YAG ceramic is tailored to mitigate ASE generated parasitic oscillations likely to occur when reaching the high gain levels expected when operating the laser head at below 200K temperatures. Not only the emission cross section will increase by a factor around 2, but also the absorption cross section by a similar factor. This will allow us to drastically reduce the pump brightness requirements down to 5 kW/cm? when comparing with the actual RT operated amplifier head (for which up to 20 kW/cm? where requested). Such brightness will be spatially homogeneously delivered over a 6.6 cm? elliptical pump area by the new pump source manufactured by Lastronics (Jena, Germany). When coupled with the RT head, our 30 Joules milestone will be within reach. We will review progress on Lucia and present first experimental results obtained with this new laser head.

WS100-4, Session 2

Demonstration of a prototype laser amplifier concept scalable to energies suitable for inertial fusion energy projects

Paul D. Mason, Klaus Ertel, Saumyabrata Banerjee, Paul J. Phillips, Justin Greenhalgh, Cristina Hernandez-Gomez, John L. Collier, Rutherford Appleton Lab. (United Kingdom)

An inertial fusion energy (IFE) reactor will require megajoules of laser energy to be delivered in multiple beams onto a target, with the pulse energy of a single beam expected to be of order 10 kilojoules in the infrared. In the HiPER project each beam is planned to be made up of an array of sub-aperture beamlets each delivering kilojoule level nanosecond pulses. For energy production to be viable the wall-plug efficiency of the laser must be between 10 % and 15 % and it must operate at pulse repetition rates of order 10 Hz. A conceptual design for an efficient kJ-class diode-pumped solid-state laser (DPSSL) system based on cryogenic gas-cooled multi-slab ceramic Yb:YAG amplifier technology has been developed at STFC, as a building block towards a MJ-class source for HiPER. In order to confirm the viability of this concept a prototype amplifier, DiPOLE, scaled to deliver 10 J at 10 Hz with 25% optical-to-optical (o-o) efficiency has been developed at the Central Laser Facility (CLF). To date amplification of ns-pulses at 1030 nm has successfully demonstrated output energies in excess of 10 J with o-o conversion efficiencies greater than 20% and operation up to 10 Hz repetition rate, with performance tested over a range of operating temperatures from 90 to 175 K. In this paper we review progress on the DiPOLE project, describing the most recent performance results from the prototype amplifier, and plans to scale up the design to provide 100 J pulses at 10 Hz. The scaled-up system will provide a stepping-stone towards development of a kJ-class laser enabling further de-risking of key technologies, necessary for a future IFE laser.

WS100-5, Session 2

High-energy-class cryogenically cooled Yb:YAG multi-slab laser system with low wavefront distortion suitable for fusion driver prototyping

Martin Divoky, Pawel Sikocinski, Jan Pilar, Antonio Lucianetti, Ondrej Slezák, Magdalena Sawicka, Tomas Mocek, Institute of Physics of the ASCR, v.v.i. (Czech Republic)

In this contribution, detailed modeling of 100 J cryogenically cooled Yb:YAG laser system based on multi-slab technology is presented. The laser system consists of ~100 mJ front-end that is followed by 4-pass power amplifier consisting of two identical laser heads. The gain of the active medium is calculated at 160 K by ray-tracing code that includes polychromatic rays, temperature dependent material parameters, and amplified spontaneous emission. Propagation of the laser beam is calculated by solving diffraction integrals in the MIRÓ code. Amplification of the beam in the amplifier chain is calculated by Frantz-Nodvik equation. Wavefront deformations upon propagation are calculated by using measured transmitted wave distortion of typical optical components, calculated thermal maps of the active medium and Seidel aberrations. Thermal maps were obtained in COMSOL at first by modeling He gas flow in the cooling loop to obtain heat transfer coefficient between Yb:YAG slabs and cooling gas and at second by using the heat transfer coefficient to calculate cooling and thermal distribution in the slab. Calculated output wavefront is corrected by PZT controlled deformable mirror. The surface of the mirror is optimized using calculated influence functions and custom actuator arrangement.

Calculation predicts output energy of 110 J with optical-to-optical efficiency of 27%. The laser is designed to operate at 5 J/cm2 average extraction fluence and maximum fluence is below 10 J/cm2. Total wavefront distortion of 8 lambda is corrected to less than lambda/5 by the deformable mirror.

WS100-6, Session 2

Characterisation of a low temperature and adhesive free bonding technique for optical materials

Nicola L. Beveridge, Gooch & Housego Plc (United Kingdom) and Univ. of Glasgow (United Kingdom); Mark Gardner, Gooch & Housego Plc (United Kingdom); James Hough, Christian J. Killow, Univ. of Glasgow (United Kingdom); Peter E. MacKay, Gooch & Housego Plc (United Kingdom)

The epoxy and cement free bonding of optical interfaces without exposure to high temperatures and pressures is a technology offering a number of advantages. The bond resulting from such fusion is

of extremely high optical quality, and its mechanical properties are capable of withstanding harsh conditions such as spacecraft launch forces and cryogenic temperatures. Whilst the technique has already been proven in space missions for jointing materials such as fused silica and low expansion optical glasses, it is only now being developed into a commercial process. The potential applications for such a technology include true zero order wave plates, light weight space assemblies, optical assemblies requiring precision alignment and large scale crystal quartz rotators.

The ability to bond certain materials, e.g. fused silica, has now been successfully established within Gooch and Housego and is an option available for commercial products. Bonding composite optical assemblies in this manner provides improved optical alignment performance as the assembly is far less sensitive to temperature variations compared with an assembly using more traditional epoxies and cements. Results demonstrating some of the key features of this technology will be presented.

The realisation of a crystal quartz rotator with dimensions that exceed the present maximum size of hydrothermally grown synthetic quartz is critical for the use of laser fusion as an alternative power source. The development time and cost to produce larger crystals is prohibitive. The jointing technique described above is proposed for use in the fabrication of a large crystal quartz rotator, producing substrates of sufficient size with requirements including extremely high optical quality and the ability to withstand high incident laser powers.

As well as the jointing of dissimilar materials and jointing large surface areas, a variety of different surface preparation processes are currently being investigated in order to obtain a robust production method. Here we present progress made in the development of a new technology and early results from characterisation tests.

WS100-7, Session 2

Cryogenic cooling system for large lasers

Jean-Paul Perin, CEA Grenoble (France)

The Extreme Light Infrastructure (ELI) will be a new scientific European infrastructure devoted to scientific research in lasers field, dedicated to the investigation and applications of laser-matter interaction at the highest intensity level (more than 6 orders of magnitude higher than today's laser intensity). The ELI project, a collaboration of 13 European countries, will comprise three branches: Ultra High Field Science that will explore laser-matter interaction, attosecond Laser Science designed to conduct temporal investigation of electron dynamics in atoms, molecules, plasmas and solids at attosecond scale, High Energy Beam Science devoted to the development and usage of dedicated beam lines with ultra short pulses of high energy radiation. Using DPSSL (Diode Pumped Solid State Lasers) as pumping technology, PW-class lasers with enhanced repetition rates are developed. Each of the Yb YaG amplifiers will be diode-pumped at a wavelength of 940 nm. This is a prerequisite for achieving high repetition rates (light amplification duration 1 millisecond and repetition rate 10 Hz). The efficiency of DPSSL is inversely proportional to the temperature, for this reason the slab amplifier have to be cooled at a temperature in the range of 100K-170K with a heat flux of 1 MW*m-2. This paper describes the thermo-mechanical analysis for the design of the amplification laser head, presents a preliminary proposal for the required cryogenic cooling system and finally outlines the gain of cryogenic operation for the efficiency of high pulsed laser.

The main points to be solved are

• The control of turbulences of the gas in the cooling channels. This turbulences can introduce some diffraction which have 2 bad effects, the power losses and the front wave deformations.

• The design of the amplifiers has to take into account the thermal contraction and the thermo mechanical stresses due to the gradient and the difference of thermal expansion coefficient.

• An economic study has been done which show that the cryogenic cooling, even with a more complex design, has a working cost smaller than at room temperature.

WS100-9, Session 3

HiPER project target studies on shock ignition: design principles, modeling. energy scaling, risk reduction options *(Invited Paper)*

Stefano Atzeni, Alberto Marocchino, Angelo Schiavi, Univ. degli Studi di Roma La Sapienza (Italy); Xavier Ribeyre, Guy Schurtz, Edouard Le Bel, Univ. Bordeaux 1 (France); Mauro Temporal, Univ. Politécnica de Madrid (Spain)

We describe recent progress in the study of shock-ignited laser fusion targets.

In previous publications we had identified a window in laser parameter space for the ignition of a simple, small target (with fuel mass of less than 0.3 mg), previously designed for fast ignition. We had also studied aspects of the robustness to parameter deviation from nominal values as well as to hydrodynamic instabilities and non uniform irradiation. Aspects of the scaling with target size had also been discussed. Recent work aimed at improving target and laser modelling (e.g., by considering targets with a more realistic structure, and 3D irradiation schemes) and increasing target robustness. In particular, we show that the separation of the stages of fuel compression and hot spot creation, typical of shock ignition, introduces some design flexibility when scaling targets to higher size. This can be exploited in the future, once limitations set by laser-plasma instabilities and hydrodynamic instabilities will be assessed experimentally. We have determined analytic scaling laws for the different design options, and used detailed numerical simulations to generate the relevant gain curves. We are studying ways to reduce the growth of Rayleigh-Taylor instabilities both at the ablation front and at the hot-cold fuel interface. Concerning irradiation schemes, we have analyzed ways to increase robustness to laser errors and target misplacement; we are also studying polar-drive schemes, which could be used to test shock ignition on the NIF or LMJ lasers, originally designed for indirect-drive laser fusion. In the final part of the presentation we will discuss a few open issues for shock ignition, requiring specific experimental and theoretical efforts.

WS100-10, Session 3

Estimation of yield stability for repetition-rate HiPER shock-ignition targets using start-to-end hydrodynamic simulations

Angelo Schiavi, Alberto Marocchino, Stefano Atzeni, Univ. degli Studi di Roma La Sapienza (Italy)

We present results of a numerical investigation campaign for HiPER baseline targets driven by a shock-ignition laser pulse[1]. High-gain 1D hydrodynamic implosions were studied in order to identify a reference point design for this ignition scheme. A parametric scan of capsule illumination pattern has been conducted in order to maximise laser intensity uniformity, while keeping to a minimum shot-to-shot fluctuations and total drive energy[2].

The irradiation stability requirements, i.e. laser beams with a wide and flat radial profile, are in contrast with cross-beam energy transfer requirements, e.g. non-overlapping beams with narrow beam waist [3]. This issue is presented and discussed in the framework of HiPER project.

Start-to-end 2D hydrodynamic simulations coupled to fully 3D laser raytracing were performed for selected cases in order to assess fusion yield dependance on main irradiation parameters. The importance and accuracy of transport mechanisms currently implemented in hydrocodes is discussed. A caveat on the use and interpretation of start-to-end simulations of capsule implosion is proposed.

References

[1] Atzeni S. et al, PPCF 53 035010 (2011).

[2] Schiavi A. et al., EPL 94 35002 (2011)

[3] Froula D.H. et al., PRL 108, 125003 (2012)

WS100-11, Session 3

Non-local electron transport: models and impact on direct-drive shock-ignition targets

Alberto Marocchino, Stefano Atzeni, Angelo Schiavi, Univ. degli Studi di Roma La Sapienza (Italy)

Shock Ignition schemes require laser pulses with intensities exceeding 10^15 W/cm^2. At such intensities a few percent of electrons have a mean free path longer than the characteristic temperature gradient scale length. The classical Spitzer-Harm thermal conduction operator (even including flux-limitation) is no longer appropriate, non-local transport models need to be used to catch the underlying physics.

We will first briefly compare two non-local electron transport models: Schurtz-Nicolai-Busquet [1] and the Colombant-Manheimer-Goncharov [2,3] model. We will highlight few key numerical aspects and discuss their use in inertial fusion hydrodynamic codes.

We will then focus on the use such models in shock ignition target simulations. In the first place we will discuss the effect of non-local transport during the ablation phase where electron transport affects temperature and density evolution and generation of the ablation pressure. In the second place we will discuss how the models can also treat preheating of the target payload.

References

[1] G. Schurtz et al. Physics of Plasmas 7 10 (2000) pp. 4238-4249.

[2] W. Manheimer et al. Physics of Plasmas 15 8 (2008) pp. 083103

[3] D. Colombant et al. Journal of Computational Physics 229 11 (2010) pp. 4369-4381

WS100-12, Session 3

Lattice structure effects on fast electron transport in advanced fusion targets

Paul McKenna, David MacLellan, David C. Carroll, Ross J. Gray, Univ. of Strathclyde (United Kingdom); Alex P. L. Robinson, Rutherford Appleton Lab. (United Kingdom); Michael Desjarlais, Sandia National Labs. (United States); Haydn Powell, Univ. of Strathclyde (United Kingdom); Nicola Booth, Rutherford Appleton Lab. (United Kingdom); Graeme Scott, Univ. of Strathclyde (United Kingdom); Matthias Burza, Lund Univ. (Sweden); Xiaohui Yuan, Univ. of Strathclyde (United Kingdom); David Neely, Rutherford Appleton Lab. (United Kingdom); Claes-Goran Wahlström, Lund Univ. (Sweden)

The physics of the transport of large currents of fast, relativistic electrons in dense matter underpins many topics in high intensity laser-solid interactions (including warm dense matter and ion acceleration) and is central to the fast ignition approach to inertial confinement fusion. The propagation of laser-generated fast electrons within a dense target is subject to self-generated resistive magnetic fields, which affect the beam divergence, and resistive instabilities, which give rise to filamentation of the beam. Understanding, and where possible engineering, the evolution of target resistivity can therefore play a key role in controlling fast electron beam transport properties.

By comparing the fast electron transport properties of various allotropes of carbon, it recently has been shown that the highly ordered lattice structure of diamond results in a transient state of warm dense carbon with metallic-like conductivity, at temperatures of the order of 1–100 eV, which leads to the suppression of resistive instabilities in electron beam transport [1]. By contrast, significant beam filamentation is observed in less ordered forms of carbon for the same laser drive conditions. The ordered lattice structure of warm-dense diamond (which is maintained over picosecond timescales) is found to be a key factor in defining its high conductivity and hence the properties of energetic electron beam transport.

We report on new followup experimental results (using the Vulcan laser) and related numerical simulations, which demonstrate an intensity dependence of the onset of resistive instabilities and the effects of resistive magnetic fields. We should that both beam transport effects are sensitive to the target material resistivity-temperature profile. The results influence the choice of materials, and in particular the choice of allotrope of a given material, for use in advanced inertial fusion schemes such as Fast Ignition.

[1] McKenna et al, Phys. Rev. Lett. 106, 185004 (2011)

WS100-13, Session 3

Atomic physics modeling and applications for inertial fusion energy

Emilio Minguez, Univ. Politécnica de Madrid (Spain); Ricardo Florido, Pablo Martel, Jesus Garcia, Rafael Rodriguez, Juan M. Gil, Miguel A. Mendoza, Univ. de Las Palmas de Gran Canaria (Spain)

Fundamental research and modelling in plasma atomic physics continues to be essential for both providing basic understanding and advancing on many different topics relevant to high-energy-density systems community. In this work we will discuss several results, with emphasis in recent applications to ICF. For instance, the collisional-radiative package ABAKO/RAPCAL has been used for detailed calculations of population kinetics and spectroscopic diagnosis of direct-drive ICF targets. Thus, we briefly review the atomic kinetic calculations as well as the simulation of the ionization balance of well-characterized elements for ICF plasmas. With a different purpose, i.e. to provide fast computation of mean and frequency-dependent emissivities and opacities for hot and dense LTE single- and multi-component plasmas and allow an easy coupling to a potential hydrodynamic code, a new average-atom screened-hydrogenic model (ATMED code) has been developed. It relies on a new set of screening constants adjusted to fit a large database of 105 experimental and computed ionization potentials and excitation energies. This model can be also used to compute the plasma EOS and shock Hugoniot curves.

WS100-15, Session 3

New fast and accurate numerical method for laser-produced relativistic electrons beams transport in the context of ICF: applications to fast and shock ignition

Philippe Nicolai, Jean-Luc Feugeas, Mickael Touati, Jerome Breil, Bruno Dubroca, Joao J. Santos, Xavier Ribeyre, Univ. Bordeaux 1 (France); Sergei Y. Gus'kov, P.N. Lebedev Physical Institute (Russian Federation); Vladimir T. Tikhonchuk, Univ. Bordeaux 1 (France)

One major issue to address in Inertial Confinement Fusion (ICF) is the detailed description of the kinetic transport of laser generated fast electrons in the time and space scales of the hydrodynamic evolution of the imploded target.

We have developed, at CELIA, a fast reduced kinetic model for relativistic electrons transport based on the angular moments of the relativistic Fokker-Planck equation, the M1 model [1]. This model takes into account the slowing down of fast electrons through collisions with plasma electrons (free and bounded), plasmons and the elastic scattering of fast electrons on plasma ions and electrons. The self-consistent magnetic and electric fields are computed thanks to a generalized Ohm law. This module has been implemented into the 2D radiation hydrodynamic code CHIC [2]. The M1 model is used as well as for the Fast Ignition (FI) than for the Shock Ignition (SI) schemes.

A recent experiment of relativistic electrons transport through Aluminium foils is analyzed thanks to this multi-scales tool. Because of its computing speed, various initial configurations have been tested to reproduce experimental data. In addition, due to its structure, the effects of electric and magnetic fields can easily be highlighted and so the resistive fast electrons losses are directly compared to the collisional losses.

Concerning Shock Ignition scheme, it is shown that the energy transfer by fast electrons from the corona to the compressed shell is a important mechanism in the creation of ablation pressure. A 30 keV energy electron beam of 2 – 5 PW/cm2 energy flux may create a pressure amplitude of more than 300 Mbar within few tens of ps in a pre-compressed solid material [3]. The dynamics of the ablation layer and the shock evolution are also presented in realistic configurations.

References :

[1] B. Dubroca et al., Eur. Phys. J. D 60, 301 (2010)

[2] J. Breil et al., J. Comp. Phys. 224, 785 (2007).

[3] S. Gus'kov, X. Ribeyre, M. Touati, Ph. Nicolaï, J.-L. Feugeas and V. Tikhonchuk, Submitted to Phys. Rev. Letters

WS100-16, Session 3

Full scale modellIng of fast ignition with particle-in-cell simulations

Frederico Fiuza, Univ. Técnica de Lisboa (Portugal) and Lawrence Livermore National Lab. (United States); Ricardo A. Fonseca, Univ. Técnica de Lisboa (Portugal) and Instituto Superior de Ciencias do Trabolho e da Empresa (Portugal); Warren B. Mori, Univ. of California, Los Angeles (United States); Luis O. Silva, Univ. Técnica de Lisboa (Portugal)

The integrated modeling of fast ignition of ICF targets is important to understand the electron source requirements and the optimal laser/target configuration for ignition. We have used the hybrid-PIC algorithm of OSIRIS [F. Fiuza et al., PPCF 53, 074004 (2011)] to model fast ignition in a self-consistent way at realistic densities, spatial and temporal scales. We will present a detailed analysis of the laser absorption and the fast electron source characterization for different laser and target parameters in 2D and 3D. Integrated electron transport and energy deposition calculations for realistic ignition laser parameters (100 kJ, multi-ps) will be shown and used to identify the electron source requirements for ignition. The control of the electron energy distribution and divergence by using of an external magnetic structure and/or multiple radially incident short pulses will be discussed, showing the possibility of achieving conditions consistent with ignition.

WS100-17, Session 3

High ablation presure shock-wave driven by supra-thermal electrons

Xavier Ribeyre, Univ. Bordeaux 1 (France); Sergei Y. Gus'kov, P.N. Lebedev Physical Institute (Russian Federation); Mickael Touati, Jean-Luc Feugeas, Philippe Nicolai, Vladimir T. Tikhonchuk, Univ. Bordeaux 1 (France)

Hot electron transport and energy deposition are crucial in many problems of inertial fusion confinement (ICF) physics. Relativistic electrons are used to ignite a deuterium tritium assembly in the fast ignition scheme. However, all conventional schemes of central ignition must to avoid of hot electrons that may preheat the fuel and spoil the efficiency of shell implosion. The electrons with moderated energies in the 100 keV range are produced in laser pulse interaction with the plasma corona if the laser intensity exceeds the value of 1 PW/cm2 for the wavelength of 351 nm. The parametric instabilities such as stimulated Raman scattering and two plasmon decay are considered as the major source of hot electrons. The situation is however different in the shock ignition where the laser spike is launched at the late implosion stage. The shell is already sufficiently dense to stop the electrons with the energies of the order of 100 keV, and thus, to prevent the fuel preheat [1]. Moreover, such hot electrons, may contribute significantly to creation of the high ablation pressure [2], which is one of main challenges of shock ignition.

In this paper, we present an analytical model of the shock wave formation by an intense beam of mono-energetic electrons in a dense plasma [3]. It is based on the self-similar solution of isothermal expansion of a finite mass of plasma [4]. The specificity of the electron driven ablation is that it is non-stationary. The fast electron range is independent on the plasma temperature and thus the energy deposition zone moves out of the dense plasma along with the expanding material. Thus the pressure generation proceeds in two phases. During the loading time of a few tens of picosecond, before the rarefaction wave is formed, the pressure grows linearly with time. This time depends mainly of the electron stopping range. The shock wave is formed at this stage. The second phase corresponds to expansion of a continuously heated fixed mass of plasma. The plasma pressure at the contact with a non-ablated material deceases in square toot of time, and the shock wave is effectively disconnected from the driver. Thus the loading time is optimal duration for the fast electron injection. For the electron beam energy flux of 3 – 5 PW/cm2 and the electron energy of 30 – 50 keV, shock wave amplitude more than 300 Mbar can be maintained for 200 – 300 ps in a pre-compressed solid material. The efficiency of the energy coupling of the electron beam to the shock wave is estimated to be of 8% if the beam duration is comparable to the loading time. The analytical results are confirmed by numerical simulations with the radiation hydrodynamic code equipped with a kinetic module [5] describing the fast electron transport in a dense plasma.

[1] X. Ribeyre et al, Phys. Plas. Contrl. Fusion 51, 015013 (2009)

[2] S.Yu. Gus'kov et al, Sov. J. Quantum Electronics 13, 498 (198)

[3] S. Gus'kov, X. Ribeyre, M. Touati, Ph. Nicolaï, J.-L. Feugeas and V. Tikhonchuk, Phys. Rev. Lett. Submitted

[4] V. S. Imshennik, Sov. Phys. Doklady 5, 263 (1960)

[5] Ph. Nicolaï et al., Phys. Rev. E 84, 016402 (2011)

WS100-35, Session PS

Study of converging spherical shock wave with a finite Mach number in the context of shock ignition

Alexandra Vallet, Xavier Ribeyre, Vladimir T. Tikhonchuk, Univ. Bordeaux 1 (France)

The shock ignition (SI) scheme is the one chosen in the HiPER (High Power laser Energy Research) project. It consists in a separation of the compression and the ignition phases of the target evolution. First, the target is compressed at a low velocity (< 300 km/s). This allows to obtain a high density central core while keeping under control the hydrodynamic instabilities. However, the hot spot conditions are not sufficient to achieve ignition. Then, a shock is launched to create a high pressure hot spot and ignite the fuel.

It is possible to use the self-similar solution of Guderley to describe the interaction of the ignition shock with the hot spot. This model considers a high Mach number shock and neglects the counter-pressure of the hot spot. However, a typical simulation of SI shows that the pressure in front of the shock needs to be accounted for. We extend in this work the model of Guderley to finite Mach number shock waves.

Using a perturbative approach proposed in Ref. [1], we develop a solution as a power series in (c0/Us)2 , with c0 being the initial speed of sound and Us being the shock velocity, of hydrodynamics equations for a perfect gas in spherical geometry. The zeroth order solution is the self-similar solution of Guderley. The first order correction to this solution accounts for the effects of the shock strength on the final hot spot state.

Whereas it was constant in the Guderley asymptotic solution, the amplification factor of the shock ?(t) ? d Us / d Rs now varies in time. The shock acceleration increases during the converging phase and then decreases during the divergent phase. The factor ?(t) is iteratively calculated so that the solution does not undergo any singularity apart from the position of the shock. The values obtained are consistent with those found in the literature [1].

The correction for finite Mach number affects mainly the density and pressure of the flow after the rebound of the shock. The final density ratio is no more constant but decreases with time. We observe also a sizeable reduction of the pressure behind the diverging shock. Thus, if the hot spot pressure is too high before the launch of the ignition shock, the shock is less efficient and the final density and pressure are lower.

This solution allows to define an analytical criterion for SI which takes into account the initial pressure of the hot spot. This criterion involves the alpha particles energy deposition, the electronic conduction losses and the radiative losses. We obtain a relation between the initial areal density, pressure and velocity of the shock. Good agreements are obtained with numerical simulations of SI implosion with HiPER

baseline target.

[1] N. F. Ponchaut, et al. On imploding cylindrical and spherical shock waves in a perfect gas. Journal of Fluid Mechanics, 2006.

WS100-36, Session PS

Collisionless laser absorption due to parametric instabilities in the shock ignition

Ondrej Klimo, Czech Technical Univ. in Prague (Czech Republic); Xavier Ribeyre, Vladimir T. Tikhonchuk, Univ. Bordeaux 1 (France)

Shock ignition concept for inertial confinement fusion implies launch a strong shock with the high intensity laser spike into imploding shell. The laser intensity in plasma corona is above the threshold for the parametric instabilities providing thus conditions for strong nonlinear effects. Our 1D kinetic simulations of laser plasma interaction in such a regime show that after a transient period of a strong non-stationary scattering, the laser plasma interaction enters in an asymptotic regime where a significant part of the incident laser flux is absorbed in plasma and transformed in hot electrons. The repartition of the absorbed energy and spectral characteristics of the scattered radiation are presented. For the laser intensity of 8PW/cm2, the total absorption is ? 70%; about 20% of absorption takes place in 1/16th of the critical density and 50% – at the quarter critical density, 38% are due to the SRS, which produces electrons with the temperature about 35 keV, and 12% are due to cavitation, which produces a more isotropic distribution of hot electrons with the temperature of 30 keV.

WS100-37, Session PS

Laser-plasma interaction investigation on a planar target at the conditions relevant to shock ignition

Federica Baffigi, Gabriele Cristoforetti, Petra Koester, Luca Labate, Leonida A. Gizzi, Istituto Nazionale di Ottica (Italy); Fabrizio Consoli, Riccardo De Angelis, Associazione Euratom-ENEA (Italy); Luca Antonelli, Maria Richetta, Univ. degli Studi di Roma Tor Vergata (Italy); Dimitri D. Batani, Gerard Malka, Philippe Nicolai, Yohann Maheut, Yong-Joo Rhee, Giulia Folpini, Univ. Bordeaux 1 (France); Jan Badziak, Zosia Kalinowska, Jerzy Wolowski, Tomasz Chodukowski, Tadeusz Pisarczyk, Marcin Rosinski, P. Paris, Institute of Plasma Physics and Laser Microfusion (Poland)

The shock ignition (SI) scheme is a promising approach to inertial confinement fusion for the simplicity of the target and laser parameters required and for its potential high gain. In order to produce the shock pressure needed for ignition, the laser spike intensity has to be sufficiently high, above the threshold for the nonlinear interaction of the laser pulse with the large scale plasma produced during compression. Parametric instabilities and the subsequent generation of fast electrons are expected to occur, which could affect significantly the efficiency of shock wave generation. An experiment aimed at investigating the effect of fast electrons on the shock wave pressure was conducted at the PALS laser facility in Prague. The experiment was performed in a planar geometry. The shock was launched in a multilayer target with the main laser beam (?=438 nm) at an intensity up to 1016 W/cm2. A long scale plasma was created before the arrival of the main laser pulse using an auxiliary beam (?=1315 nm) and the timing between the two beams was varied. Both beams were smoothed using phase plates in order to ensure a homogeneous beam profile in a large focal spot. A set of diagnostics was used for the characterization of the laser-plasma interaction, the generated fast electrons and the shock wave. Here we concentrate on spectroscopy and calorimetry of the backscattered radiation. In particular, harmonic and half-harmonic emission as a signature of parametric instabilities such as Stimulated Raman Scattering and Two Plasmon Decay were observed. Both these instabilities can result in the production of supra-thermal electrons. In addition, X-ray measurements with a CCD working in single-photon regime are presented. K? emission from a Cu layer inside the multilayer target as well as the high energy X-ray spectrum give information about the fast electron energy and conversion efficiency. Furthermore, fast particle energy spectra were monitored by CVD diamond detectors.

WS100-39, Session PS

Overview and latest proposals in SBS PCM based IFE technology featuring self-navigation of lasers on injected direct drive pellets

Milan Kalal, Czech Technical Univ. in Prague (Czech Republic); Ondrej Slezák, Czech Technical Univ. in Prague (Czech Republic) and Institute of Physics of the ASCR, v.v.i. (Czech Republic); Hong Jin Kong, KAIST (Korea, Republic of); Neil B. Alexander, General Atomics (United States)

The current status will be reviewed of a recently proposed novel approach to inertial fusion energy (IFE) technology, where phase conjugating mirrors (PCM) generated by stimulated Brillouin scattering (SBS) are employed in combination with a special target displacement compensation system to implement an automatic self-navigation of every individual laser beam onto injected IFE pellets. This novel technology is of a particular importance to the direct drive schemes of pellet irradiation, which is the basis of a number of IFE project (e.g., HiPER). If successful in its full scale realization, this aiming scheme would greatly reduce the technical challenges of adjusting large and heavy optical elements during each shot in an IFE reactor, where a typical repetition rates are several Hertz. Featuring no moving parts, this technology would allow for a higher number of laser drivers to be employed. Operating with lower energies (< 1 kJ) such laser drivers would be easier to design for the required repetition rate. Using this approach would also eliminate damage of the reactor chamber windows caused by a perpendicular SBS mechanism.

The latest achievement in the gradual step-by step development of this technology is a conceptual design for the removal of the unconverted basic laser harmonic. This is needed since the corresponding schemes already developed to deal with this issue, e.g., for Laser MegaJoule (LMJ - France) or National Ignition Facility (NIF - USA) are not applicable in the SBS PCM IFE technology. For this purpose a special Faraday isolator was recently proposed. For the basic harmonic propagating in both directions (to be removed during its second pass) it will work in its classical configuration. The higher harmonic (propagating only in the backward direction) will be allowed to pass through. In order to deal with problems associated with a rather high absorption in the case of higher harmonics, a special tandem version of this Faraday isolator was suggested. This special design is going to be tested soon experimentally in Korea.

Having the unconverted harmonic removal problem solved, a serious development of the SBS PCM based laser driver can be started to establish an upper limit of energy at which the required laser beam parameters would be still acceptable. This energy limit comes from the use of SBS PCMs to self-navigation steering of the laser beams to the target, which means that spatial filtering cannot be employed to take care of the laser beam quality. The value of the upper energy level obtained would determine the number of laser drivers needed for a direct drive fusion facility working in the expected 5-10 Hz repetition regime of an IFE power plant.

WS100-40, Session PS

Low-density targets and transient processes in subcritical plasmas

Nataliya G. Borisenko, P.N. Lebedev Physical Institute (Russian Federation); Lidia Borisenko, P.N. Lebedev Physical Institute (Russian Federation) and Moscow State Univ. (Russian Federation); Yuri Merkuliev, Andrey Orekhov, P.N. Lebedev Physical Institute (Russian Federation)

In early high-power irradiation experiments on foams the structure of the target was reported to have slight if any influence on the major results. Further the distinct unpredicted effects appeared to be connected with initial solid structure, especially when the diagnostic means achieved higher resolution and accuracy.

Plasma partial transparency, non-linear behavior as well as plasma emittance and dynamics effects that could be attributed to the target structure influence are analyzed in order to work out the target fabrication and characterization procedures. Those should be adequate (necessary and enough) for preparing low-density solids as laser targets. An attempt of proposing standard is made. The target structure examples fall into 3 differing categories: aerogels, foams, nano-snow layers. By requirement they could intersect to form composites. The parameters of the modern targets have grown quite extreme from the point of view of the solid state physics. The unprecedented combination of uniformity and density could reach gaseous one. This enables the profound study of subcritical plasmas even with the basic laser wavelength including searching for transient processes in subcritical plasmas.

WS100-41, Session PS

Reflectivity measurement of spherical crystal used as K-alpha imagers

Pierre Forestier-Colleoni, Univ. d'Orléans (France); Luca Antonelli, Univ. Bordeaux 1 (France); Dimitri D. Batani, Univ. degli Studi di Milano-Bicocca (Italy); Giulia Folpini, Univ degli Studi di Milano-Bicocca (Italy); Sébastien Hulin, Univ. Bordeaux 1 (France); Sergei A. Pikuz, Cornell Univ. (United States); Joao Jorge Santos, Univ. Bordeaux 1 (France); Luca Volpe, Univ. degli Studi di Milano-Bicocca (Italy)

K-alpha emission is a commonly used diagnostics to study the generation of fast electrons in matter. K-alpha emission is characteristic of fast electron propagation: the fast electrons remove inner electrons in the atoms, which then emit a x-ray photon of given energy as the gap in the K-shell un

lled eject. Spherically bent crystals allow making images of the K-alpha source in the laser-irradiated target onto a detector (in our case a CCD camera). This allows to measure the K-alpha source size which is very useful to understand the divergence of the electron's beam. The measurement of the absolute reflectivity of K-alpha crystals used as imagers is also essential in order to be able to evaluate the total number of emitted K-alpha photons, and then the number of fast electrons generated in the interaction between the high intensity laser beam and the target. With experiment, we measured the reflectivity of tree crystals of quartz used to reflect the K-alpha of the Copper. Cu targets, 10 m in dept, were irradiated with the laser ECLIPSE of CELIA at intensity of 1018W/cm2. Emitted photon were recorded using an Andor X-ray CCD which was either placed in the image plan of the crystal, or directly exposed to the X-ray ux (single photon counting). For all shots a second X-ray CCD (Princeton, also in single photon counting mode) was uses as reference. The comparison between signals recorded with and without the crystals allow to means the reflectivity. The detailed geometry and line shape of K-alpha as well as the spectral resolution of the crystal and of the CCD must be take into account.

WS100-42, Session PS

Experimental studies on the relativistic high-current electron beam transport in the context of fast ignition: main results and perspectives for the Petal-LMJ facility

Joao Jorge Santos, Univ. Bordeaux 1 (France); Dimitri D. Batani, Univ. degli Studi di Milano-Bicocca (Italy); Sophie D. Baton, Ecole Polytechnique (France); C. Beaucourt, Univ. Bordeaux 1 (France); Farhat N. Beg, Univ. of California, San Diego (United States); Nathalie Blanchot, Tiberio Ceccotti, Alexis Casner, Commissariat à l'Énergie Atomique (France); Arnaud Debayle, Univ. Politécnica de Madrid (Spain); Fabien Dorchies, Jean-Luc Feugeas, Univ. Bordeaux 1 (France); Shinsuke Fujioka, Osaka Univ. (Japan); Claude Fourment, Univ. Bordeaux 1 (France); L. Gremillet, CEA (France); José J. Honrubia, Univ. Politécnica de Madrid (Spain); Sébastien Hulin, Univ. Bordeaux 1 (France); Jean-Luc Miquel, Commissariat à l'Énergie Atomique (France); Alessio Morace, Univ. degli Studi di Milano-Bicocca (Italy); Peter A. Norreys, Rutherford Appleton Lab. (United Kingdom); Philippe Nicolai, Univ. Bordeaux 1 (France); Frederic Perez, Ecole Polytechnique (France); Hiroshi Sawada, Univ. of California (United States); Hans-Peter Schlenvoigt, Friedrich-Schiller-Univ. Jena (Germany); R. H. H. Scott, Rutherford Appleton Lab. (United Kingdom); Vladimir T. Tikhonchuk, Xavier Vaisseau, Benjamin Vauzour, Univ. Bordeaux 1 (France); Mingsheng Wei, General Atomics (United States)

We will present a summary of the recent experiments on fast electron transport performed in the framework of the HiPER experimental validation program.

We will particularly focus on the characterization of the electron stopping power in dense matter ranging from solid targets to warm-dense matter. The energy losses due to both collisional and collective mechanisms have been experimentally discriminated. Numerical simulations, benchmarked by the experimental data, show that the transition from collision-dominated to resistive field-dominated energy loss occurs for a fast-electron current density jh going above the level of a few 1011 A/cm2. According to analytical estimations, for the jh ≈ 1014 A/cm2 regime of a full-scale fast ignition shot, the resistive stopping power should remain limited to ~ 1 keV/μm, a value not undermining the nuclear fuel ignition.

The efficient coupling of the intense laser energy into the nuclear fuel core can nevertheless be limited to the intrinsic electron beam divergence. Magnetic collimation of the electron beam is foreseen either by self-generated or exterior magnetic fields on the level of a few kT.

Experimental evidence of efficient self-magnetic field assisted beam guiding has been achieved in both cylindrical-driven compressed targets (resistivity gradient regime) and in a dual collinear laser beam configuration (beam radial-inhomogeneity regime). Laser-generated exterior magnetic field is also foreseen as a promising strategy for producing collimated electron beam propagation and will be soon experimentally tested.

Experimental perspectives deployable on the Petal-LMJ facility, in operation from 2015, will allow to extend the previous studies to the level of the kJ intense laser energy coupled to compression driving laser energy on the level of several 100 kJ.

WS100-18, Session 4

Experiments on shock ignition: what has been done what are the next steps to prepare demonstration on LMJ/PETAL *(Invited Paper)*

Dimitri D. Batani, Univ. Bordeaux 1 (France)

In 2007 Betti et al. proposed a novel approach to ICF. It consists of igniting the target by a very strong converging shock (P ≈ several hundreds of Mbar at the ablation surface), produced by intense laser spikes (up to 1e16 W/cm2), which must hit the target at the end of the compression phase. The scheme represents a very attractive solution for the HiPER project since it maintains the advantages of direct drive, of separating the ignition and compression phases, and it is substantially compatible with present day laser technology (used to build NIF and LMJ). A proof of principle of shock ignition could be realized on LMJ within the next decade.

In the talk, I will present:

i) the results of preliminary experiments conducted at PALS in order to study shock generation and laser-plasma interaction in an intensity regime which is relevant for shock ignition, and

ii) the status of the discussion within HiPER on the shock ignition roadmap, including the plan for future experiments on European laser facilities (PALS, LULI, Orion, LIL, etc) and for finally approaching SI demonstration on LMJ.

Experiments at PALS were done using two beams, with time duration 300 ps. The first beam, at intensity ≈ 1e13 W/cm2, was used to create a ≈ 1 mm preformed plasma, and the second, at ≈ 1e16 W/cm2, to create the final strong shock. Several diagnostics were employed to characterize both the preformed plasma (Phase 1), and the shock formation and laser-plasma interaction (Phase 2). In Phase 1, they included X-ray deflectometry and Optical interferomerty for the plasma density profile, and X-ray spectroscopy to get plasma temperature.

In Phase 2, we used an Energy Encoded pin-hole camera to measure plasma extension, characterize its emission, but also give evidence of the presence of hot electrons; shock cronometry to measure the ability to produce a strong shock and the effect of the extended plasma corona on the laser-shock coupling; X-ray (K-?) imaging again for hot electrons; optical spectroscopy and calorimetry to get the amount of backreflected light from parametric instabilities (SRS, SBS, TDP).

WS100-19, Session 4

Beamtime opportunities at LMJ/PETAL

Thierry Massard, Commissariat à l'Énergie Atomique (France)

No Abstract Available

WS100-20, Session 4

The Orion laser: update and applications

Andrew Randewich, AWE plc (United Kingdom)

The Orion laser at AWE, currently being commissioned, will be used to conduct research into high energy density physics phenomena, such that occur at the heart of a nuclear explosion. The building houses a large neodymium glass laser system and a target chamber in which the high energy density physics experiments are conducted. Orion will generate matter many times denser than solid – at temperatures up to 10 million degrees. It will give scientists the opportunity to study densities and temperatures found nowhere else on earth.

Designed primarily to support AWE's core work, Orion is also being made available for collaborative academic research, for which the first call for proposals has been issued.

Orion will deliver up to 5 kJ at 351 nm in 10 1-ns duration beams with flexible pulse-shaping, and up to 500 J in ~0.5 ps at 1053 nm in each of two short-pulse beams, one of which is currently frequency-doubled (at reduced aperture) to give increased contrast.

When fully commissioned it will have an extensive suite of optical, X-ray, charged-particle and neutron diagnostics, many of which are deployable in diagnostic insertion devices.

This talk will consist of an update on recent progress and describe initial experiments.

WS100-21, Session 4

Diagnostics of warm dense matter parameters by high-resolution x-ray spectroscopy of hollow ions

Anatoly Y. Faenov, Joint Institute for High Temperatures (Japan) and Joint Institute for High Temperatures (Russian Federation)

The properties of high energy density plasma are under increasing scrutiny in recent years due to their importance to our understanding of the properties of hot plasma in inertial confinement fusion devices, stellar interiors, the cores of giant planets, and so on. Experiments with an ultrahigh-contrast femtosecond laser have yielded a new type of X-ray emission spectra with a complex structure consisting of resonance lines against the quasicontinuous background. Some recent work has shown that such spectra can only be accounted for by considering the radiation emitted by multiply charged hollow (empty K shell) ions in ultradense plasma. Hollow ions could be especially effectively produced when matter is heated by X-rays. In such case electrons in the inner shells are ionized before the valence electrons. Advances in free-electron laser (FEL) technology have made possible the creation of condensed matter consisting predominantly of hollow atoms. Recently it was demonstrated that such exotic states of matter, which are very far from equilibrium, can also be formed by more conventional optical laser technology when the laser intensity approaches the radiation dominant regime.

This review discusses the observation of the spectra of hollow ions in laser-produced plasma and emphasized opportunities of hollow ion spectra-based diagnostic techniques for warm dense matter investigations.

WS100-22, Session 4

Investigation of efficiency of laser radiation energy transport into the shock wave with the use of a planar target

Tadeusz Pisarczyk, Jan Badziak, Andrzej Kasperczuk, Zosia Kalinowska, Tomasz Chodukowski, Piotr Parys, Marcin Rosinski, Jerzy Wolowski, Institute of Plasma Physics and Laser Microfusion (Poland); Sergei Y. Gus'kov, Nikolai N. Demchenko, P.N. Lebedev Physical Institute (Russian Federation); Luca Antonelli, Dimitri D. Batani, Univ. Bordeaux 1 (France); Petra Koester, Istituto Nazionale di Ottica (Italy); Jiri Ullschmied, Institute of Plasma Physics of the ASCR, v.v.i. (Czech Republic); Pawel Pisarczyk, Warsaw Univ. of Technology (Poland)

One of the most important researching aspects related to the shock ignition, is the generation mechanism of ablative pressure during irradiation of thermonuclear target, in which processes of non-collisional radiation absorption (e.g. resonant absorption, stimulated Raman scattering, two-plasmon decay of light wave, stimulated Brillouin scattering or filament instability) play an important role. A burning question concerns not only the above mentioned absorption processes participating in the total laser light absorption, but particularly the influence of the energy transport realized by the fast electrons in formation of the shock wave generated ablative pressure. In order to obtain a satisfying answer to this important question, the plasma researches at PALS are carried out within the LASERLAB projects by scientific teams using various diagnostics.

We are presenting the experimental results devoted to the investigation of energy transfer from PALS iodine laser beam to shock wave generated in planar targets. Two kinds of targets were applied: (i) Al and Cu massive and (ii) layered planar targets (consisting of a massive Cu target and a thin layer made of light material - CH). Three-frame interferometry and measurement of crater parameters were used as the main diagnostic tools. For more information about the ablative plasma parameters and the fast electron generation the spectroscopic measurements in the X-ray range (using 2D imaging) and measurements of the ion emission by ion collectors and Thomson analyser were applied.

The investigations have been performed at laser intensities in the range of 10^{15-16} W/cm^2 that together with PALS laser pulse duration of 200 ps (FWHM) correspond to the same parameters of a laser action to generate igniting shock wave in ICF target. The basic (lambda=1.315 um) and third harmonic (lambda=0.438 micron) of radiation at the energy of 50-300 J were applied. The intensity of laser pulse at the fixed energy was varied by varying the laser beam radius. The main goal of the experiments was to investigate the effect of the fast electrons energy transport on the ablation pressure formation and shock wave generation. The 2D numerical simulations including the calculation of the resonant absorption of laser radiation and fast electron generation as well as fast electron transport have been performed to support the explanation of experimental results.

WS100-23, Session 4

Efficient laser-driven generation of ultra-intense ion beams for fast ignition in the LICPA accelerator

Jan Badziak, Slawomir Jablonski, Piotr Raczka, Tadeusz Pisarczyk, Institute of Plasma Physics and Laser Microfusion (Poland)

Laser-induced cavity pressure acceleration (LICPA) is a novel scheme of acceleration of dense matter having a potential to accelerate heavy macro-particles or ion beams with the energetic efficiency much higher than the achieved so far with other methods [1]. In this scheme, a projectile placed in a cavity is irradiated by a laser beam introduced into the cavity through a hole, and then accelerated along a guiding channel by the thermal pressure created in the cavity by the laser-produced plasma or by the photon pressure of the ultra-intense laser radiation trapped in the cavity. This contribution reports results of particle-in-cell (PIC) simulations of light ion generation in the LICPA accelerator in which a picosecond circularly polarized laser pulse of intensity ~(1÷5)?10^21 W/cm^2 irradiates a few micrometer thick target placed in the accelerator cavity. It is shown that with a 100 kJ/2ps laser driver, the accelerator is capable of producing quasi-monoenergetic light ion beams (H^+, Be^4+, C^6+ or Al^13+) of the mean ion energy ~ 40÷50 MeV/amu, the beam energy fluence ~ 2GJ/cm^2 and the total beam energy ~ 40 kJ which meet fairly well the requirements for ion fast ignition of fusion targets.

1. J. Badziak et al., Phys Plasmas 19, 053105 (2012).

WS100-24, Session 4

Relativistic high-current electron beam stopping power characterization in warm-dense compared to cold-solid matter

Xavier Vaisseau, Dimitri D. Batani, Univ. Bordeaux 1 (France); Sophie D. Baton, Ecole Polytechnique (France); Farhat N. Beg, Univ. of California, San Diego (United States); Jim D. Bonlie, Lawrence Livermore National Lab. (United States); Sugreev Chawla, Univ. of California, San Diego (United States); Mireille Coury, Univ. of Strathclyde (United Kingdom); Jonathan R. Davies, Univ. of Rochester (United States); Arnaud Debayle, Univ. Politécnica de Madrid (Spain); Luca Fedeli, Univ. degli Studi di Milano-Bicocca (Italy); Robert Fedosejevs, Univ. of Alberta (Canada); Claude Fourment, Univ. Bordeaux 1 (France); Shinsuke Fujioka, Osaka Univ. (Japan); Lorenzo Giuffrida, Univ. Bordeaux 1 (France); Ross J. Gray, Univ. of Strathclyde (United Kingdom); Sébastien Hulin, Univ. Bordeaux 1 (France); José J. Honrubia, Univ. Politécnica de Madrid (Spain); Leonard C. Jarrot, Univ. of California, San Diego (United States); Gregory E. Kemp, The Ohio State Univ. (United States); Shaun M. Kerr, Univ. of Alberta (Canada); Kun Li, Instituto de Plasmas e Fusão Nuclear (Portugal); Paul McKenna, Univ. of Strathclyde (United Kingdom); Harry S. McLean, Lawrence Livermore National Lab. (United States); Mianzhen Mo, Univ. of Alberta (Canada); Alessio Morace, Univ. degli Studi di Milano-Bicocca (Italy); Motoaki Nakatsutsumi, Ecole Polytechnique (France); Philippe Nicolaï, Univ. Bordeaux 1 (France); Jaebum Park, Pravesh K. Patel, Lawrence Livermore National Lab. (United States); Jonathan Peebles, Univ. of California, San Diego (United States); Haydn Powell, Univ. of Strathclyde (United Kingdom); Yong-Joo Rhee, Korea Atomic Energy Research Institute (Korea, Republic of); Hiroshi Sawada, Univ. of California, San Diego (United States); Hans-Peter Schlenvoigt, Lab. pour l'Utilisation des Lasers Intenses (France); Anna Sorokovikova, Univ. of California, San Diego (United States); Richard B. Stephens, General Atomics (United States); Vladimir T. Tikhonchuk, Mickael Touati, Benjamin Vauzour, Univ. Bordeaux 1 (France); Luca Volpe, Univ. degli Studi di Milano-Bicocca (Italy); Mingsheng Wei, General Atomics (United States); Vincent Yahia, Ecole Polytechnique (France); Joao J. Santos, Univ. Bordeaux 1 (France)

In the fast ignition (FI) scheme for inertial confinement fusion, a laser produced relativistic electron beam (REB) is used to achieve ignition of a D-T capsule. The settlement of this procedure requires a deep understanding of the REB transport, in particular the way it looses energy over the standing-off distance between the source and the ignition hot spot. In this context three similar experiments were performed on the Pico2000 laser (LULI, France) and on the JLF-Titan laser (LLNL, USA) facilities. A REB was generated by ps laser beams (10^19 W.cm-2 at LULI, 10^20 W.cm-2 on Titan) in a multilayer target with an aluminium propagation layer, compressed by a counter propagative planar shock induced by a ns laser beam (LP beam). In this geometry, the target areal density and the collisional stopping power consequently remain constant when comparing solid and compressed cases for targets of the same initial thickness. A variation of the stopping power due to compression can therefore be associated with a modification of collective effects.

K? yield measurements were made in order to monitor the fast electron source and the fraction of RE crossing the propagation layer. For a current density jh~10^10 A.cm-2 in the propagation layer, no striking difference was observed in solid and compressed samples as a function of the propagation layer areal density. Hybrid simulations of REB transport showed that even though collisional processes dominated in these experimental conditions, resistive effects were responsible for one third of the energy losses. When increasing the current density up to 10^11 A.cm-2 in the propagation layer, it was observed that the fraction of electrons crossing the propagation layer was smaller in compressed targets when compared to solid samples of thickness >60µm. This is interpreted as a rise of the resistive stopping power in compressed cases.

Two configurations related to the LP beam focal spot diameter were also explored:

for a 200 ?m diameter spot, the difference between solid and compressed cases was more important, but so was the divergence of the REB due to 2D effects.

For a 750 ?m diameter spot, corresponding to a true 1D compression, the difference between solid and compressed cases was not as important as in the previous case. This is however in agreement with numerical simulations showing that for a REB current density jh > 10^11 A.cm-2, resistive losses are important enough to be observed.

To avoid direct interaction of the REB with the coronal plasma, a cone shaped target has been proposed as a potential design for fusion targets. In this context, a fourth experiment concerning the study of cone target perturbation and of REB generation and transport in warm and dense matter was submitted on the Pico2000 laser system. The preliminary part of this experiment concerning the study of the shock collision/sliding along the cone walls and its breakout was already performed. Experimental results consisting in radiographies and shock breakout measurements are shown, as well as hydrodynamic simulations.

WS100-26, Session 5

Roads to power plant physics and technology in laser fusion energy systems under repetitive operation *(Invited Paper)*

José Manuel Perlado Martín, Univ. Politécnica de Madrid (Spain); Javier Sanz, Univ. Politécnica de Madrid (Spain) and Univ. Nacional de Educación a Distancia (Spain); Jesús Alvarez Ruiz, David Garoz Gomez, Raquel Gonzalez-Arrabal, Nuria Gordillo, Carlo Guerrero, Ovidio Peña, Antonio Rivera, Emma del Rio, David Cereceda, Javier Fernández Tobías, Alberto Fraile, Univ. Politécnica de Madrid (Spain); Rafael Juarez, Univ. Politécnica de Madrid (Spain) and Univ. Nacional de Educación a Distancia (Spain); Nuria Moral, Univ. Politécnica de Madrid (Spain); Consuelo Sánchez, Univ. Nacional de Educación a Distancia (Spain); Gonzalo Vallés, Marta Velarde, Maximo Victoria, Miguel Panizo, Alejandro Prada, Angel Rodríguez-

Páramo, Univ. Politécnica de Madrid (Spain)

Along the Preparatory and Business case phases of HiPER (High Power laser Energy Research) an extensive work has been performed to design roads and specific research for proposing facilities for Inertial Fusion Energy by Lasers at different levels under a shock ignition and dry wall options. With contributions from different European groups, Engineering Burst facility and Power Reactor (both Prototype and Demonstration) have been developed. Our results are related to two different levels: i) research in each one of the key questions (areas/component) from fundamental and applied physics for technology; ii) integration of our available answers (including those in (i)) into a Power Plant System for defining progressive designs. This work will present the differences in design, physics and technology according with the level of proposed facility. Those magnitudes include from burnup to thermo mechanical and damage responses of materials, fluidynamics and coolant, tritium generation and connection with tritium cycle, accident analysis after evaluation of activation and radionuclide concentrations, safety and radioprotection. The chamber filling of gas at low density will be assessed, in addition to advanced First Wall materials (W nano and C based) and final optics damage with proposals to prevent such effect. The proposals for coolant (LiPb or Li) and the chamber+blanket design will be presented, remarking the differences that for each one of the potential roads there will be from the technology basic physics. In particular, the effect of manufacturing and validation of W-nano as first wall, proposals of avoid damage in final optics, a power plant design based on LiPb, simulation models for trititum diffusion, LiPb analysis and determination of coefficients, FeCr modeling of damage and atmospheric dispersion of T have been calculated and will be presented.

WS100-27, Session 5

Development of target injector and repetition fusion chamber systems for HiPER

Bedrich Rus, Institute of Physics of the ASCR, v.v.i. (Czech Republic); David Neely, Martin K. Tolley, Rutherford Appleton Lab. (United Kingdom); Chris Edwards, Science and Technology Facilities Council (United Kingdom); Mike Tyldesley, Rutherford Appleton Lab. (United Kingdom); Vladimir Kolarik, Institute of Scientific Instruments of the ASCR, v.v.i. (Czech Republic); Tomas Papirek, Martin Hlavac, DELONG INSTRUMENTS a.s. (Czech Republic); José Manuel Perlado Martín, Univ. Politécnica de Madrid (Spain); Jaroslav Nejdl, Colorado State Univ. (United States); Jiri Polan, Michaela Kozlová, Pavel Homer, Institute of Physics of the ASCR, v.v.i. (Czech Republic); Petr Havlik, SWELL, s.r.o. (Czech Republic); Martin Kopecky, SWELL s.r.o. (Czech Republic); Jean-Paul Perin, CEA Grenoble (France); Steve Sanders, Oxford Technologies Ltd (United Kingdom); Richard Haley, Lewis MacFarlane, Nuclear Technologies plc (United Kingdom); Neil B. Alexander, General Atomics (United States)

Recent effort in development of repetition rate injection of cryogenic targets for laser fusion energy HiPER project will be reviewed. Analysis of prospective solutions of a precise injector capable to achieve velocities of the cryogenic fusion pellet of up to 1000 m/s was made, followed by a prototype demonstrator of the injector front end using magnetic Halbach-type linear guideway and gas-gun arrangement. We have also carried out extensive numerical simulations of integrity and of deformations of the fusion pellet during its acceleration and subsequent “cruise” towards the chamber center, showing that the pellet will suffer only minor deformations not exceeding several microns. Another issue that has to be addressed in the design of a laser fusion energy facility is temporal synchronization of the laser with the injector as well as measurement of the actual position of the flying pellet ensuring that the laser pulse meets it in time near the desired “zero” point. Results of this analysis will be summarized, showing that tracking the target with a precision of ~10 microns, switching out pulses from an oscillator running at 100 MHz, will be adequate for performing the task. Finally we will shortly discuss solutions for “in-flight” target deflection and steering systems and a solution for extraction of fusion debris in the reactor chamber.

WS100-28, Session 5

Testing first wall materials for laser fusion reactors with laser driven ions: What can we learn?

Jesús Alvarez Ruiz, Javier Fernández Tobías, José Manuel Perlado Martín, David Garoz Gomez, Univ. Politécnica de Madrid (Spain)

The authors have already suggested that ultra intense laser systems can be a solution to the present lack of facilities to study and test plasma facing components for laser fusion reactors. The ability of ultra intense laser systems to generate short pulses of energetic particles and radiation at high fluxes can be tuned to induce in test materials similar effects to those generated in the laser fusion explosions on the first wall components. Based on computational simulations and reported scaling laws, this contribution aims at describing in detail the experimental conditions for such investigations, namely, laser pulse characteristics, laser target selection and geometry, target-to-sample distance, etc. Limitations of this technique due to the demands on the repetition rate and energy of the laser system or the selection of a specific particle from all the simultaneously generated laser induced species are addressed.

Finally, we report on the novel findings which this technique can provide not only in the laser fusion design of plasma facing components but also from a more fundamental point of view in research areas such as radiation damage and transition region between cold and warm dense matter.

WS100-29, Session 5

Theoretical modeling of carrier dynamics and damage processes in materials interacting with intense radiation sources

Tzveta T. Apostolova, Institute of Nuclear Research and Nuclear Energy (Bulgaria); Antonio Rivera, Univ. Politécnica de Madrid (Spain); Martin T. Ivanov, Institute of Nuclear Research and Nuclear Energy (Bulgaria); José Manuel Perlado Martín, Univ. Politécnica de Madrid (Spain)

We investigate radiation-matter interaction highly dominated by strong electronic excitation mechanisms. In this category we can consider radiation sources such as ultra intense laser beams, swift heavy ion irradiation and XUV and VUV pulses. These sources deposit their energy mainly to the electronic system of the irradiated material leading to a very high electronic density production. We have used quantum kinetic theory based on a generalized Boltzmann-type equation for the microscopic description of damage mechanism due to high power, ultra-fast pulse laser fields and swift heavy ion irradiation and we have applied it to bulk GaAs semiconductors and silica glass materials.

The formalism provides a detailed description of the electronic system evolution including photo-excitation and inter band ionization, impurity- and phonon-assisted photon absorption processes and subsequent relaxation of carriers via radiative recombination and carrier-lattice interactions, resulting heating, formation of free excitons and their self-trapping, as well as Coulomb scattering between two electrons leading to Auger recombination. For the case of swift-heavy ion interaction, ion projectiles with intermediate non-relativitic velocities are considered. Charge transfer and ionization across the band-gap are not taken into account at this stage.

Our approaches provide quantitative information on the electron distribution and the resulting electron density as well as damage threshold. For the case of ion irradiation we observe a high-energy tail in the Fermi-Dirac distribution. The thermodynamics of hot electrons is studied by calculating the average kinetic energy (effective electron temperature) as a function the laser intensity, pulse width and wavelength and in the case of ions - impact parameter of the ion projectile, its velocity and the charge number.

WS100-30, Session 5

Financial modeling of inertial fusion power plant applied to HiPER project

Artemis Kaliataki, Panagiotis Petrakis, Stavros Moustaizis, Technical Univ. of Crete (Greece)

The quantity that is used to make a comparison among electric energy production power plants is the Cost of Electricity per kWh (CoE). The adapted methodology for the evaluation of CoE, is mainly based on previous works in the international bibliography, concerning Inertial Fusion (IF) power plants that employ laser or heavy ion beam drivers. A computational program is developed that evaluates the CoE, when given the physical, geometrical and technical parameters of the power plant. The input data for the program are, the target gain depending on the different IF schemes (direct, fast ignitor and shock) and the laser efficiency, as a function of the laser energy. For fixed values of the (1) net electric power, (2) fusion power per unit area, that can tolerate the first wall of the reactor's chamber, (3) thermal efficiency and (4) auxiliary power efficiency, the program calculates the repetition rate, the fusion power, the thermal, the gross electric and the auxiliary power, as also, the radius of the chamber, using the appropriate cost estimation relationships accepted worldwide for this subject. The costs of the subsystems of the IF power plant are expressed with scaling relationships as functions of the operating parameters, at 1GW net electric power output. The program also allows the estimation of the values of the operating parameters for the optimum operation of the plant, by plotting the graphs of the costs as a function of the laser energy. The relationships used in the program can be adapted for the HiPER's parameters. Determining role to the cost have, the pumping laser system with a rep.rate of few Hz, the corresponding efficiency, as well as the target gain (depending on the laser IF scheme) as a function of the laser energy.

Acknowledgements

The work was supported by the European High Power laser Energy Research (HiPER) project

WS100-31, Session 5

Microtargetry for inertial fusion energy
(Invited Paper)

Martin K. Tolley, Rutherford Appleton Lab. (United Kingdom)

There is extensive international activity in pursuing laser-driven fusion as a potential source of commercial electrical power. The approach is called inertial fusion energy (IFE). This paper discusses IFE focussing on one of the primary technological challenges specifically the production of microtargets. Information presented is based on wide range of past and present coordinated activity within the main European project proposed for the realisation of IFE: HiPER [1].

After a brief introduction to IFE the targetry requirements will be discussed for an operational power plant identifying both the need for very high production numbers and some of the most demanding microtarget specifications. Current production techniques for laser-driven fusion targets will be discussed especially in the context of industrial scalability for mass production. The potential of alternative techniques will also be discussed. A forward strategy will then be presented.

The full HiPER delivery plan is complex and only its essential structure will be reviewed in this talk focussing primarily on microtarget mass production issues and risk reduction. General technical issues of significance for IFE targetry are also discussed.

[1] http://www.hiper-laser.org/index.html

WS100-32, Session 5

High rep-rate free-standing target supply system for HiPER

Elena R. Koresheva, Irina V. Aleksandrova, Igor E. Osipov, Evgeniy L. Koshelev, Andrei I. Kupriashin, Viacheslav A. Kalabukhov, Tatiana P. Tamasheva, P.N. Lebedev Physical Institute (Russian Federation); Aleksander A. Balolipetskiy, Larissa V. Panina, Russian Academy of Sciences (Russian Federation)

For target manufacturing capability and delivery for the High Power laser Energy Research (HiPER), the Lebedev Physical Institute (LPI) has proposed to use the FST layering method of the fuel layer formation within moving free-standing targets (FST) [1].

The free-standing target supply system (FST-SS) has been designed at LPI for HiPER experiments. The system capable of work in a batch mode: 100 targets fabrication and delivery with a rate of 1-to-10 Hz. In this report we discuss the design of the main building blocks and interface units of the FST-SS as well as the results of mockups testing, namely:

1. Block#1: FST layering module (LM) based on using moving free-standing spherical shells. The fine FST features are as follows:

- Small layering time for HiPER targets t < 10 s that ensures minimal tritium inventory

- Formation of isotropic ultra-fine (nano-crystalline) fuel state that ensures: (a) obtaining the cryogenic layers with inherent survival features, and (b) regular propagation of the shock wave, the front of which has to be extremely smooth.

2. Block#2: assembly device (AD) for target-&-sabot assembly in a rep-rate mode

3. Shell container (SC) is an interface unit between the fill system and Block #1. The SC is intended for arrangement and transport of a batch of free-standing targets from the fill system to the LM, and for rep-rate target loading under gravity from the SC to the layering channel. The SC is designed for loading 200 HiPER targets to the LM with 1-10 Hz.

4. Target collector (TC) is an interface unit between Block #1 and Block #2. The TC is intended for gravity loading of the cryogenic targets from the TC to the AD in a rep-rate mode.

5. Electro-magnetic coil is an interface unit between Block #2 and injector. The coil is intended for target-&-sabot pre-acceleration and high rep-rate delivery at a start position of the injector.

There were manufactured and tested the mockups of all basic and interface units of the FST-SS for HiPER, and the following important results were obtained:

1. FST-layering in a batch of spherical CH capsules was demonstrated

2. Considerable increase of the target residence time in the LM with a double-spiral layering channel was demonstrated. This fact can be used for the LM upgrade for IFE targets.

3. Experiments at 77 K demonstrated the possibility of the ferromagnetic sabot to be pre-accelerated by a single coil to 3÷8 m/s

4. Possibility of the contact-free manipulation and positioning of free-standing cryogenic targets based on quantum levitation effect was demonstrated. The experiments will be discussed.

The obtained results allow us to turn to a commercial-scale building of the target supply system based on the FST layering method for HiPER-scale polymer targets.

1. I.Aleksandrova et al., J.Phys.D: Appl.Phys. 37, 1163 (2004)

WS100-33, Session 5

The performance of the silica final lenses in HiPER experimental facility and power plant

David Garoz Gomez, Raquel Gonzalez-Arrabal, Univ. Politécnica de Madrid (Spain); Rafael Juarez, Univ. Nacional de Educación a Distancia (Spain) and Univ. Politécnica de Madrid (Spain); Jesús Alvarez Ruiz, Univ. Politécnica de Madrid (Spain); Javier Sanz, Univ. Nacional de Educación a Distancia (Spain); José Manuel Perlado Martín, Antonio Rivera, Univ. Politécnica de Madrid (Spain)

One of the main points of concern to properly achieve ignition in laser fusion facilities is the performance of the final optics (lenses) under the severe irradiation conditions that will take place in fusion facilities. We present within the framework of the European laser fusion project HiPER (High Power Laser Energy Research) the performance of the silica transmission lenses located 8 m away from direct target explosions under different operation scenarios: (i) an experimental facility for experimentation on ignition and laser performance operating in bunch mode with low yield targets (<50 MJ); (ii) a prototype power plant operating in continuous mode (24/7) but with low yield targets (<50 MJ); (iii) a demonstration power plant, i.e., a pre-commercial installation operating in continuous mode under demanding conditions (target yield >100 MJ) with an output power of about 1 GWt.

We first present the radiation fluxes and doses as well as the radiation-induced temperature enhancement and colour centre formation in final lenses assuming realistic geometrical configurations in the three scenarios under study. Based on these fluxes we determine the mechanical stresses generated by the established temperature gradients. An important outcome is that ions resulting from the target explosions must be mitigated even in the most relaxed scenario. Otherwise, the lenses would suffer fatal surface melting following one single explosion. Provided ions are efficiently mitigated, the lenses will be exposed to neutron and associated gamma irradiation. From a thermomechanical point of view both the experimental facility and the prototype power plant will not undergo fatal melting, fracture nor fatigue. However, the final lenses in the demonstration power plant will reach steady state temperatures far above realistic operational limits. The only realistic solution for a demonstration power plant with transmission final lenses will thus be to move the lenses further away from the chamber centre.

Concerning the optical absorption induced by colour centre generation the calculations indicate that efficient defect annealing takes place at the steady state temperatures reached in power plant scenarios. In the case of the experimental facility the lenses will operate at room temperature accumulating colour centres with every target explosion. Anyway the optical absorption reached during the expected lifetime of the facility will be within tolerable limits. Therefore, optical absorption does not appear as a major drawback except during the reactor startup procedure. Our results evidence the necessity of new solutions to control the startup process in an efficient way to keep the final lens temperature above the defect annealing temperature. Finally, we evaluate the effect of temperature gradients on focal length changes and lens surface deformations. In summary, we discuss the capabilities and weak points of silica lenses and propose alternatives to overcome predictable problems.

WS100-34, Session 5

Large amplitude electric fields in inertial confinement fusion capsules

Robert Bingham, Rutherford Appleton Lab. (United Kingdom); Robert A. Cairns, Univ. of St. Andrews (United Kingdom); Peter A. Norreys, Raoul M. G. M. Trines, Rutherford Appleton Lab. (United Kingdom)

Some recent experiments in inertial confinement fusion capsules suggest the existence of electric fields of more than 1010 Vm-1 over distances of the order of 10-100 nm.

Here we show that there is an analytic treatment of electrostatic shock structures which can reproduce the essential features of these experiments.

The electric field can also separate the deuterium and tritium ions during compression.

The shock heats the ions making compression to peak density difficult.

National ignition facility: status and future plans

Ed Moses, Principal Associate Director National Ignition Facility (NIF) & Photon Science, Lawrence Livermore National Lab, United States

The National Ignition Facility (NIF), the world's largest and most energetic laser system, is now operational at Lawrence Livermore National Laboratory. The NIF's 192 beams are capable of delivering 1.8-megajoule, 500-terawatt, ultraviolet laser light, over 60 times more energy than any previous laser system. The NIF can create temperatures of more than 100 million degrees and pressures more than 100 billion times Earth's atmospheric pressure. These conditions, exceeding those at the center of the sun, have never before been created in the laboratory. This facility is designed to compress fusion fuel to the conditions required for "ignition", liberating more energy than is required to initiate the fusion reaction. Success will mark the culmination of over 50 years of research and development. This talk will discuss the current status of the program to achieve ignition, presenting the most recent experimental results.

The talk will then briefly discuss an approach to generating gigawatt levels of electrical power from such a laser-driven source of fusion neutrons based on these demonstration experiments. This approach is known as Laser Inertial Fusion Energy - or LIFE. Such a source is attractive because it will be inherently safe, generate no greenhouse gases or other environmental pollutants, provide security of fuel supply to all nations, use fuel that will last for millennia, deliver large-scale baseload electricity generation, make use of the existing grid, have no need for geological waste disposal (unlike nuclear power or carbon sequestration), and will not require enrichment or reprocessing of nuclear material that could present a proliferation risk.

Fusion has, of course, been studied in the laboratory for many years. But the potential to create a net source of power has only recently been made possible - with the completion of the National Ignition Facility. This has enabled detailed design of the subsequent LIFE power plant, guided by a team of executives from the power utility industry working with scientists from across the US and internationally.

Silicon photonics: a generic technology platform for innovation in many markets

Roel Baets, Ghent Univ. and IMEC, Belgium

Since the beginning of this century silicon photonics has emerged as a prominent technology platform for high data-rate transceivers for use in optical interconnect, active optical cables and other data-communication applications. The fact that silicon photonics largely builds on existing technologies in advanced CMOS fabs proves to be an enormous lever for the rapid scientific progress in this field as well as for the rapid development of an industrial supply chain. Furthermore the ease by which high index contrast nanophotonic concepts can be exploited in this technology has led to remarkable scientific achievements as well as the potential of high density large scale integration.

The market potential of silicon photonics is not limited to data-communication but also extends to other medium- to high-volume markets.

Disposable bio-sensing chips have been demonstrated with record detection limits and are already close to commercial deployment. More generally the technology can be used in many lab-on-chip applications as well as in biomedical applications. The strong temperature dependence of silicon photonic devices can be exploited in power-efficient switches, tuning devices and beam scanners. While standard silicon photonic devices can only be used in the transparency window of silicon and siliconoxide - roughly from 1 to 4 micrometer - CMOS-compatible variations of the same technology are now being explored both for shorter bands, including the visible, as well as the wider mid-infrared range. This opens up exciting opportunities for absorption spectroscopy and Raman spectroscopy on a chip.

Nanoplasmonic antennas for spectroscopy and sensing

Mikael Kaell, Chalmers Univ. of Technology, Div. of Bionanophotonics, Sweden

Nobel metal nanostructures are well known for their exceptionally bright and tunable colors originating in surface plasmon resonance (SPR) oscillations of the conduction-electron density. The SPR phenomenon is of high current interest in a range of fields, spanning from solar energy harvesting to metamaterials. Here I will review some of of our recent work in this area, focusing on the possibility to use metal nanoparticles as optical antennas for molecular sensing and spectroscopy. Topics to be discussed include directional plasmonic antennas based on bimetallic particle dimers and nano wires, SPR biosensors based on plasmonic nanoparticle arrays, surface-enhanced Raman scattering from individual nano antennas and optical manipulation of plasmonic nano structures.